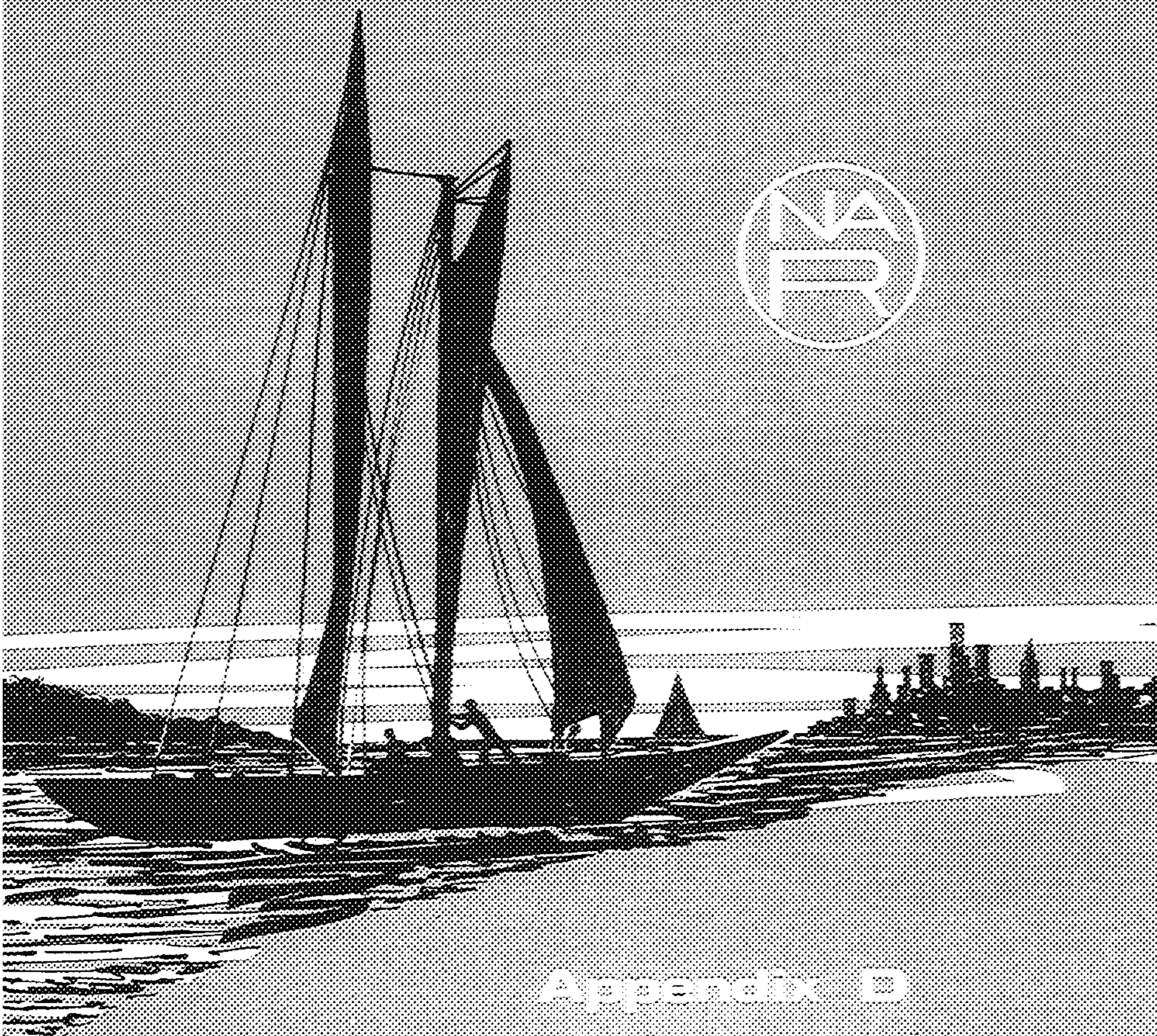
North Atlantic Regional Water Resources Study



Appendix D
Geology and Ground Water

NORTH ATLANTIC REGIONAL WATER RESOURCES STUDY COORDINATING COMMITTEE

MAY 1972

The North Atlantic Regional Water Resources (NAR) Study examined a wide variety of water and related land resources, needs and devices in formulating a broad, coordinated program to guide future resource development and management in the North Atlantic Region. The Study was authorized by the 1965 Water Resources Planning Act (PL 89-80) and the 1965 Flood Control Act (PL 89-298), and carried out under guidelines set by the Water Resources Council.

The recommended program and alternatives developed for the North Atlantic Region were prepared under the direction of the NAR Study Coordinating Committee, a partnership of resource planners representing some 25 Federal, regional and State agencies. The NAR Study Report presents this program and the alternatives as a framework for future action based on a planning period running through 2020, with bench mark planning years of 1980 and 2000.

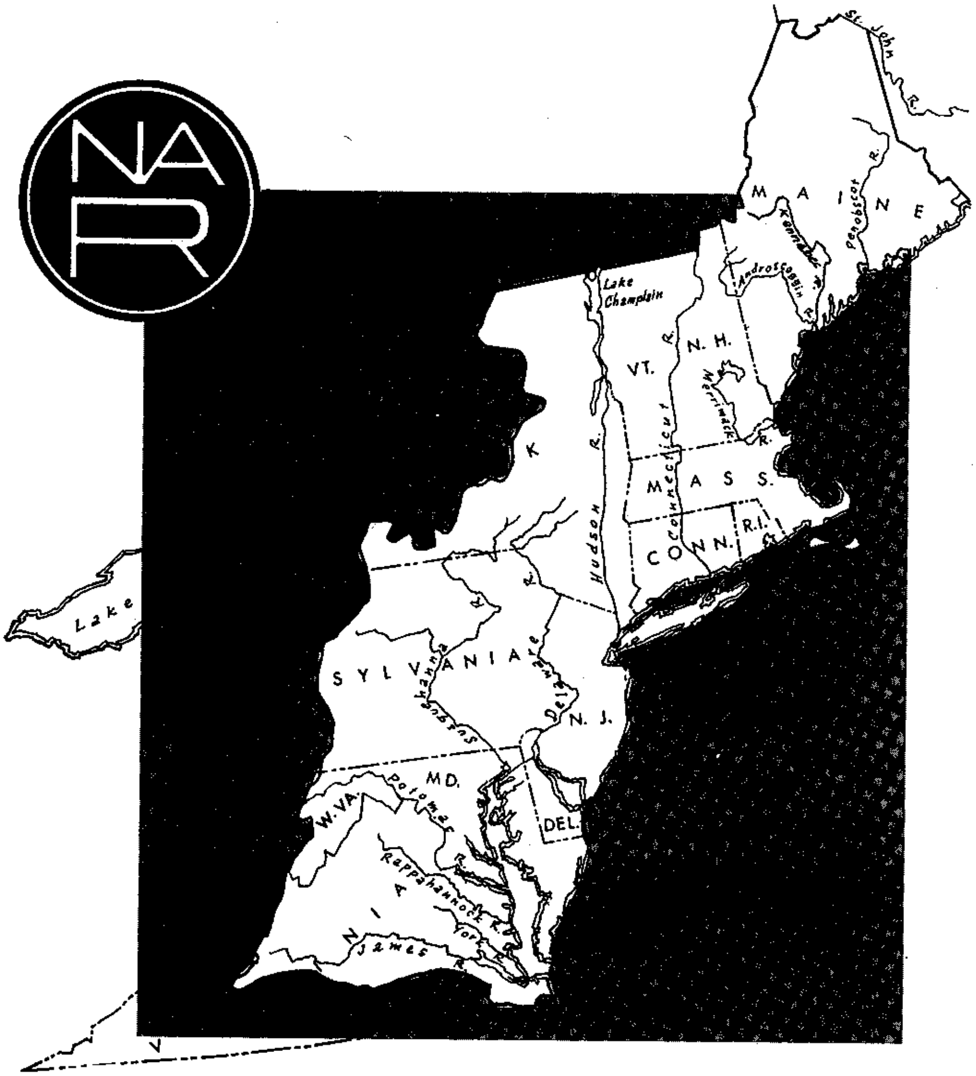
The planning partners focused on three major objectives -- National Income, Regional Development and Environmental Quality -- in developing and documenting the information which decision-makers will need for managing water and related land resources in the interest of the people of the North Atlantic Region.

In addition to the NAR Study Main Report and Annexes, there are the following 22 Appendices:

A. History of Study
B. Economic Base
C. Climate, Meteorology and Hydrology
D. Geology and Ground Water
E. Flood Damage Reduction and Water Management for Major Rivers and Coastal Areas
F. Upstream Flood Prevention and Water Management
G. Land Use and Management
H. Minerals
I. Irrigation
J. Land Drainage
K. Navigation
L. Water Quality and Pollution
M. Outdoor Recreation
N. Visual and Cultural Environment
O. Fish and Wildlife
P. Power
Q. Erosion and Sedimentation
R. Water Supply
S. Legal and Institutional Environment
T. Plan Formulation
U. Coastal and Estuarine Areas
V. Health Aspects

WATER RESOURCES NEEDS AND POTENTIALS FOR AN EXPANDING SOCIETY

Appendix D
Geology and Ground Water



Prepared by

Geological Survey
United States Department of the Interior

for the

NORTH ATLANTIC REGIONAL WATER RESOURCES STUDY
COORDINATING COMMITTEE

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PART I

GROUND WATER IN THE NORTH ATLANTIC REGION

CHAPTER I

INTRODUCTION

SCOPE AND PURPOSE

As a participating member of the North Atlantic Region water resources study group headed by the U.S. Army Corps of Engineers, the Geological Survey, Department of the Interior, was given the task of estimating the amount of ground water available on a perennial basis, providing guidelines on the utilization of ground water, and estimating the cost of its development and production. The study is devoted to an assessment of the several hydrologic provinces rather than to specific sites.

The following chapters are intended to show, among other things, that ground water and surface water are essentially one resource. The three major types of aquifers--coastal plain strata, consolidated rocks, and glacial deposits--are discussed with reference to their ground-water potential; namely, the natural recharge per unit area, the yields of wells that may be expected in the various formations, and the amount and quality of ground water that might be produced on a sustained basis. Lastly, techniques of ground-water management are discussed by which the present total available water in the system may be increased by utilizing underground storage in periods of low flow, by artificial recharge devices and by salvage of evapotranspiration loss.

The possible advantages of ground-water development, other than the advantage of increasing the volume of available water, are touched upon but not discussed in detail. The great advantage in a ground-water development is ordinarily one of costs, particularly where small to moderate supplies are needed in any one area, or where a large aggregate demand can be satisfied by well fields spread throughout a basin. A detailed assessment of costs of ground-water developments in various geological environments is given in the second section of this paper.

AREA

The North Atlantic Region is drained by streams discharging into the Atlantic Ocean. It includes the States of Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, New Jersey and Delaware, much of New York and Pennsylvania, a small part of

West Virginia, essentially all of Maryland, and that part of Virginia as far south as, and including, the James River basin. Figure D-1 shows the extent and number of river basins within the North Atlantic Region.

OUTLINE OF GEOLOGICAL PROVINCES

Figure D-2 shows the several physiographic provinces in the region. The New England, Adirondack, Piedmont and Blue Ridge provinces are underlain by crystalline and metamorphic rocks, granite, schist and gneiss, but also slate, quartzite and marble. In largest part these are Precambrian in age. The Triassic lowlands, underlain by sandstone, shale and minor volcanics, lie within the New England and Piedmont crystalline rock provinces. The Valley and Ridge province is underlain by highly folded and faulted Paleozoic limestone, sandstone and shale. Similar rocks are present in the Appalachian Plateau and the St. Lawrence Valley, but there they are almost horizontal in attitude. Highly folded Paleozoic formations make up the Taconic Highlands. The Coastal Plain is made up of sands and clays that dip gently seaward.

The North Atlantic Region is glaciated as far south as a line drawn along southernmost Long Island and westward through Pennsylvania. The consolidated rocks in the glaciated area are masked to a greater or lesser degree by till or water laid sand and gravel deposits.

CHAPTER II

THE RELATIONSHIP OF GROUND WATER TO SURFACE WATER

GENERAL

In evaluating the overall water resources of a basin, ground water and surface water should not and cannot be thought of as two separate or distantly related entities. Ground water and surface water are, in fact, two parts of the same system and withdrawal of water from one of these sources will, in many instances, merely subtract from the water available from the other source.

Rainfall and snowmelt upon the land surface is dissipated as evapotranspiration, as overland runoff and as infiltration into the ground. Overland runoff to nearby streams ceases within 3 or 4 days after a storm and is commonly lost to the system as high flow or flood flow. Nevertheless, in the humid East most streams and rivers continue to flow in ensuing periods of no rainfall, fed by seepage from the ground-water reservoir. Lacking continued contributions from the ground-water reservoir, our great rivers such as the

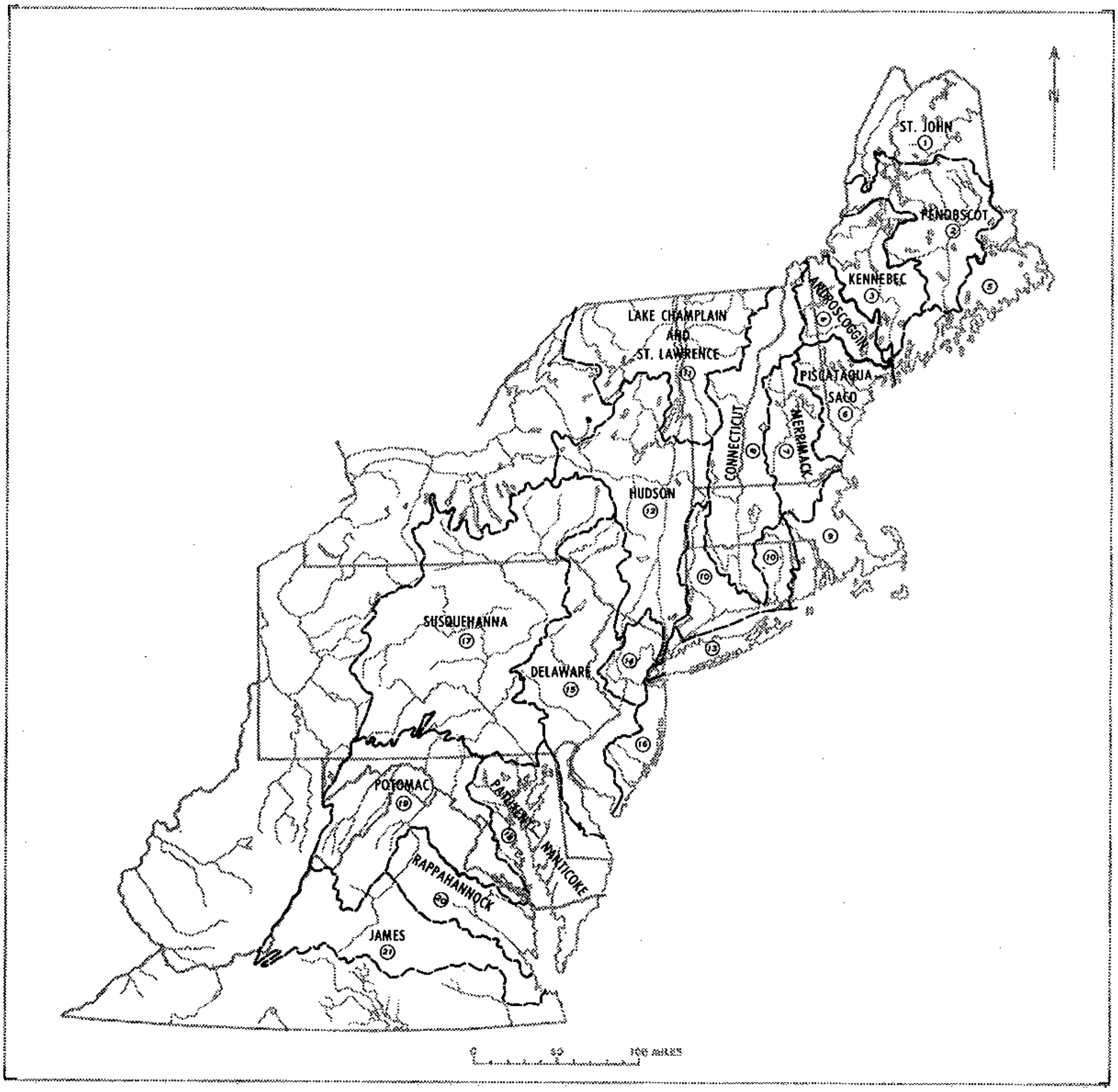


Figure D-1.--Outline of subregions and basins in the North Atlantic Region. Not titled are Basin 5--St. Croix River, Maine and Atlantic coastal area as shown; Basin 9--Narraganset Bay and Pawcatuck River drainage and Atlantic coastal area as shown; Basin 10--Thames and Housatonic River basins; Basin 13--Long Island; Basin 14--Passaic and Raritan Rivers; Basin 16--Atlantic Coast from Sandy Hook to Cape May.

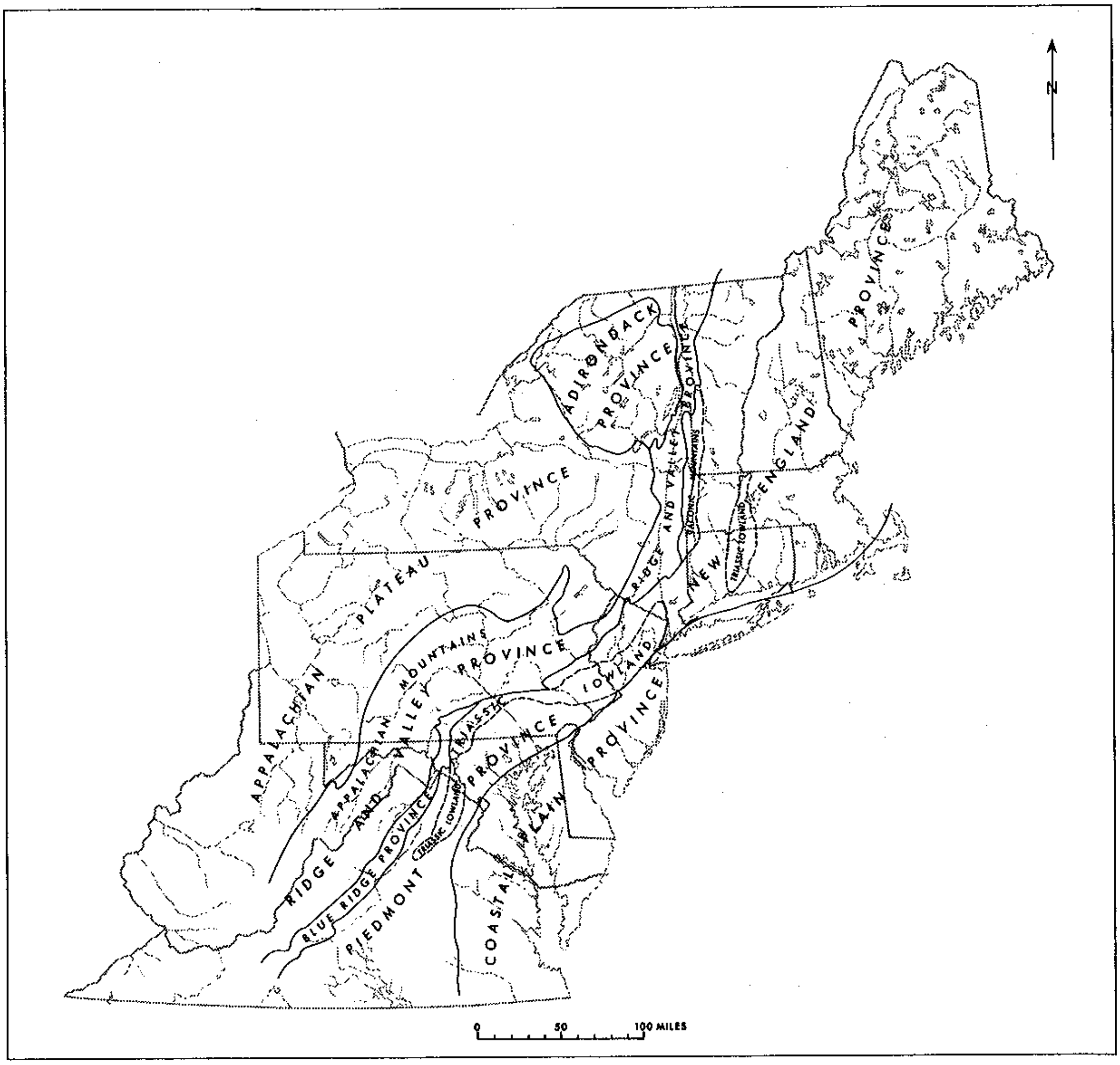


Figure D-2.--Outline of physiographic provinces in the North Atlantic Region.

Connecticut, Hudson, Delaware, Susquehanna and James would be dry gullies for long periods every year, except where marine water had migrated upstream.

During the periods of heavy rainfall or rapid snowmelt, the rate of natural recharge to the ground-water reservoir is greater than the "loss" from that reservoir by lateral flow to the streams, that is, by ground-water runoff. As a consequence the water table in interstream areas rises during periods of higher rainfall and declines slowly during periods of lesser or no rainfall. Hence, the slope of the water table toward the stream, and consequent ground-water runoff to those streams, varies to a large extent with the amount of rainfall. However, the principal yearly trends may be controlled by evapotranspiration and vary with the growing season and account for most of the variations in volume of streamflow. This simple relationship of streamflow to the ground-water reservoir is further distorted by high flows from overland runoff resulting from heavy rainfall and rapid snowmelt and may be further complicated by retention in or release of significant quantities of water from large surface reservoirs.

GROUND WATER ADDITIONAL TO SURFACE WATER

Because ground-water outflow makes up much of the streamflow, it becomes obvious that pumping of ground water from wells in a basin may simply capture ground-water outflow to the streams. Wells adjacent to streams may induce infiltration directly from the streams and wells more distant may intercept water that would seep to the streams. This may be a highly desirable alternative to pumping directly from a stream or small impoundment but no additional water may be gained and development of a significant volume of ground water by wells may have much the same effect as taking the water directly from the river.

On the other hand, the geologic and hydrologic conditions in many places are not as simple as set forth above and development of ground water will add appreciably to the total usable water supply without undesirable effects on streamflow. This may be accomplished (1) by reducing evapotranspiration from the water table, (2) by utilizing the vast amount of water in storage in underground reservoirs and (3) by increasing the storage in those reservoirs by inducing additional recharge of now wasted high flows. These techniques are applicable in most of the area but do not generally apply to artesian water in the Coastal Plain.

EVAPOTRANSPIRATION

Water budget studies referred to elsewhere in this report show that in some areas in the northeastern United States, the loss from the ground-water reservoir by evapotranspiration is equivalent to about 10 inches of rainfall per year. This is roughly half the amount of water reaching the water table in those areas and therefore roughly equal in volume to the base (dry weather) flow of the streams.

Maximum reduction of evapotranspiration loss will be effected where the water table is depressed from its position near ground surface to, say, 10 or more feet below the surface. Where low lying flat or rolling terrane is underlain by highly permeable sediments, the water table may be lowered over a wide area by heavy pumping from relatively few wells. The volume of water salvaged by reduction of evapotranspiration in such situations would be large.

Pluhowski and Kantrowitz (1) have shown that on Long Island there is an evapotranspiration loss of 11 mgd over a 30 square-mile area where the water table is about 5 feet below the surface.

Although Raber (2) seems to emphasize the dependence of trees upon available soil moisture, it is clear that some trees, shrubs, and grasses will take water from the ground-water reservoir, presumably from the capillary fringe above the water table. Most tree roots do not exceed 20 feet in depth and many are much less deep. On the other hand, Fischel (3) shows that in Kansas a diurnal water table fluctuation occurred beneath a stand of oak trees where depth to water was 43 feet below the surface. Papazafiriou and Burgy (4) have shown that in the Sierra foothills an 80% increase of water yield was observed where an oak forest was cleared and revegetated with grasses and legumes. Comparable gains were noted in a forest clearing experiment in New England (5). The greatest relative increases occurred during the critical low flow periods. A list of phreatophytes given by Robinson (6) includes alder, aspen, Bermuda grass, rayless goldenrod, Rocky Mountain juniper (swampcedar), oak, purslane, Engleman spruce, walnut, wildrye, wiregrass, and willow.

However, where pumping wells derive much of their recharge from nearby streams the water table will be lowered appreciably only in limited areas and salvage of evapotranspiration loss will be small. Further, where the water table initially lies 20 feet or more below the surface, probably only a little evapotranspiration salvage should be expected. The loss of water from bare soil by evaporation alone may be relatively small except where the capillary fringe above the water table reaches the surface. The capillary fringe may extend as much as 10 feet above the water table in fine grained sediments and as little as a few inches in coarse gravels and rock fissures.

Evapotranspiration of water normally retained by the soil will not be affected by lowering the water table.

In conclusion the subtractive effect of a ground-water development upon streamflow is reduced by the amount of evapotranspiration that is salvaged by lowering the water table and, further, that reduction of evapotranspiration loss results in an overall gain of usable water in the system. The net gain may be quite small where the water table is initially more than 20 feet below the surface.

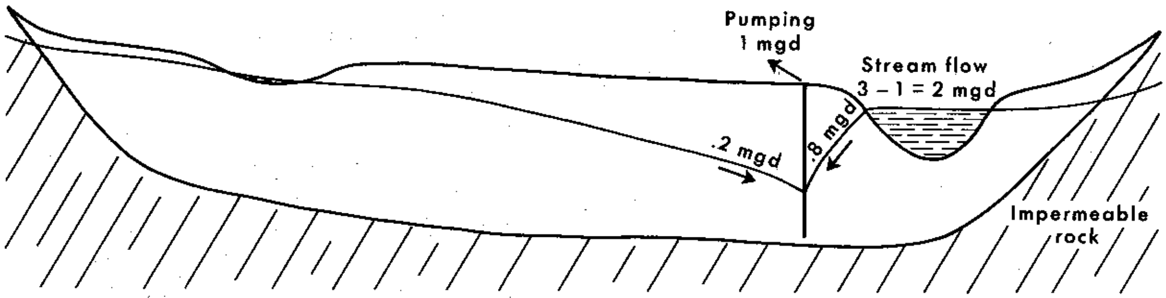
UNDERGROUND STORAGE

The time lag in the development of a cone of depression around the well or well field may be taken advantage of in providing water additional to that flowing in the streams. Assume that a well field is a half mile or a few miles distant from a major stream. In normal operation a well produces, say, 1 mgd (million gallons per day). Ground-water flow to the streams is intercepted, there is little or much flow from the stream to the well, and streamflow is reduced by 1 mgd (less salvage of evapotranspiration) (fig. D-3A and D-4A).

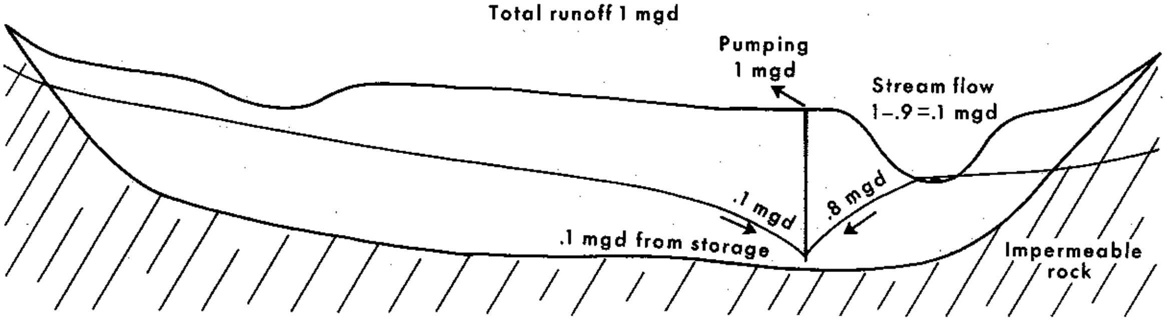
During a dry season the stream shown in figure D-3 would almost go dry due to the reverse flow of 0.8 mgd from the stream to the well, but where the well is more distant from the stream (fig. D-4B), streamflow would be reduced very little. Although the well continues to yield 1 mgd, much of the discharge is taken from storage. Time is a factor here, and in rocks with moderate to high storage potential (particularly granular sediments), the enlarging cone around the well field will grow slowly and, in fact, will not reach the stream until the period of low flow has passed. The deficiency in ground storage is then made up in the period of high precipitation with only a moderate effect upon streamflow (fig. D-4C).

The ground-water source in this example has provided 2 mgd from storage without significantly affecting the flow of the stream at its critical low flow stage. Where this management procedure is followed, additional water is provided to the system at the time of low flow at which time that flow is considered to be a measure of the dependable water resources of the basin. As noted the deficiency is made up at a later period of excess supply. The parallel to the functioning of a surface-water reservoir is obvious.

1/2 mile or a few miles distant



A. NORMAL RAINFALL PERIOD



B. LOW RAINFALL PERIOD

Figure D-3.--Sketches showing effect on streamflow of a pumping well close to a stream. Pump discharge in the low rainfall period (B) is almost entirely stream water.

more than a "few" miles distant

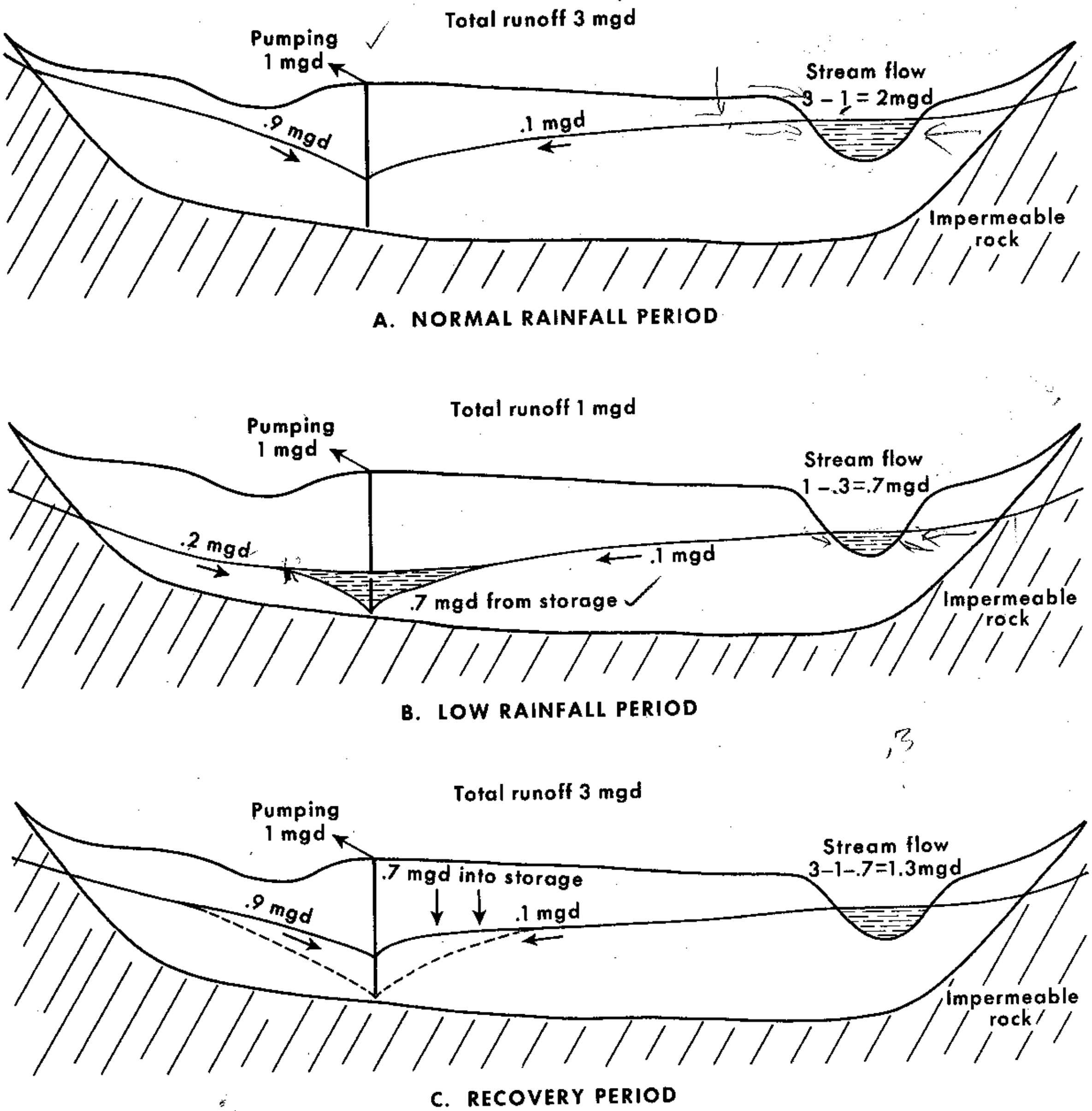


Figure D-4.--Sketches showing well system designed to rely heavily upon infiltrating river water at time of high flow (A), to draw upon underground storage at times of low flow (B) and in the succeeding higher flow period, to again draw heavily upon river water as a source of municipal supply and to recharge the underground reservoir.

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ARTIFICIAL RECHARGE

Large ground water deficiencies resulting from heavy storage withdrawal may also be compensated for by artificial recharge measures. Increasing water availability only during the wet months may possibly be helpful for satisfying some special needs but the real importance of artificial recharge will be in providing additional storage that can be drawn upon in times of critical low flow of the streams. This topic is discussed in some detail in a subsequent part of this report.

Some underground reservoirs with poor hydraulic connection with major streams and small areas of recharge may contain considerable water in storage. These may be utilized intermittently, say, every few years, without significantly affecting streamflow. As discussed later, billions of gallons of water, now in "dead" storage, are available from some glacial deposits for essentially short term use. From place to place, certain sandstone and limestone reservoirs can be drawn down sharply, thus also making available short-term withdrawals of billions of gallons of water. Considerable recovery will take place later by infiltration of local streams and rivulets during wet seasons but if extremely heavy withdrawals are made, the reservoirs may require more than one season to recover fully.

The storage capacity of crystalline rocks is large in the aggregate but average yields of deep wells in those rocks is low, less than 100 gpm (gallons per minute), and the usage of such rock units as reservoirs would be generally impractical except for smaller supplies.

However, wells recharged in large part by infiltration from the adjacent stream will not contribute any substantial volume of unused storage.

SUMMARY

Summarizing the foregoing discussion, and excepting the artesian water in the Coastal Plain, ground-water production from wells located near streams will have somewhat the same effect as pumping directly from the stream. Ground-water developments from well fields located some distance back from major streams will subtract from total annual flow (assuming no reuse factor), but the effect on streamflow will be at its maximum at stages later in time than the time of lowest flow. In such developments the overall effect on streamflow is reduced, perhaps sharply, through reduction of evapotranspiration and by inducing additional recharge in the high flow season. The result is a gain of usable water in the system. Ground-water reservoirs with poor hydraulic connections with the major drainage system may be pumped down in periods of need with only small effect on streamflow. This also brings about a gain of total usable water in that these reservoirs will be refilled in largest part by local recharge from precipitation during high flow periods, much as surface reservoirs are.

CHAPTER III

GROUND WATER IN THE COASTAL PLAIN DEPOSITS

GEOLOGY

The Atlantic Coastal Plain Province within the study area extends from Long Island through the James River basin in Virginia (plate 1A). It comprises an area of about 18,500 square miles of land east and southeast of the Fall Line in the States of New York, New Jersey, Pennsylvania, Delaware, Maryland, and Virginia. The rocks making up the Coastal Plain consist of unconsolidated sedimentary formations, Cretaceous to Pleistocene in age (table D-1), consisting chiefly of clay, marl, silt, sand, and gravel.

The sediments of the Coastal Plain were deposited under alternating marine and terrestrial conditions. This cyclic condition created an alternation of fine and coarse deposits as a result of which there is a general interfingering of the two types of deposits and commonly an imperceptible grading of one type of deposit with the other. In general, the coarser deposits are to the west and the finer deposits to the east.

The several aquifers are not everywhere continuous throughout the Coastal Plain but most of them are widely enough distributed to be mapped over large areas.

The unconsolidated Coastal Plain rocks were deposited on a bedrock surface that is inclined to the southeast and east at an average slope of 75 feet per mile. This surface is an undulating, stream-eroded surface that was downwarped (to the southeast and east) at the onset of the Cretaceous deposition and further downwarped during subsequent depositional periods. The sediments form a wedge-shaped mass in cross section that thins to a vanishing point along the Fall Zone and thickens to 8,000 feet or more, as along the east coast of Maryland (table D-1). The lowermost beds have a dip of 40 feet per mile; the younger rocks have progressively lesser dips and the uppermost beds have a dip of less than 10 feet per mile. The artesian formations crop out in narrow bands that are more or less parallel to the Fall Line.

TABLE D-1 - AQUIFERS IN THE NORTH ATLANTIC COASTAL PLAIN

Aquifers	Distribution	Dip ft/mile	Maximum Thickness	Remarks
Nonmarine Cretaceous Aquifer				
Patuxent, Arundel, Patapsco, Raritan, and Magothy formations (Early to Late Cretaceous)	L. I., N. J., Del., Md., and Va.	40	6,000 ft. in Md. 1,700 ft. on L. I.	Fresh water zone ranges from 12 to 85 miles in width and is reached at about 1,300 ft. below the surface at its maximum width in Maryland and New Jersey
Englishtown Aquifer (Late Cretaceous)	N. J. & Del.	38	160 ft.	Reached at 1,000 ft. at Toms River, N. J.
Wenonah-Mount Laurel Monmouth Aquifer (Late Cretaceous)	N. J., Del. & Md.	35	110 ft.	Reached at 2,150 ft. at Atlantic City
Aquia-Rancocas-Vincentown Aquifer (Eocene-Paleocene)	N. J., Del., Md., & Va.	25(N.J.) 12(Va.)	230 ft.	Formations more or less glauconitic
Kirkwood Aquifer (Miocene(?))	N. J.	25	600 ft.	Formation generally 60 to 100 ft. thick
Cohansey-Columbia Aquifer (Miocene (?) - Pleistocene)	L. I., N. J., Md., Del., & Va.		500 ft.	Formation thickest on L. I. and in N. J., and as little as 30 ft. thick in Virginia

HYDROLOGY

Ground water in the Coastal Plain Province is obtained from the unconsolidated sedimentary rocks of Cretaceous and younger ages except for a very few wells along the Fall Zone that obtain water from the underlying bedrock. Ground water occurs under both artesian and water-table conditions in each of the unconsolidated aquifer units. Those units older than the Pliocene are under artesian conditions except in and near their outcrop belts. Water in the Pliocene-Pleistocene aquifers occurs chiefly under water-table conditions. Water in the Miocene(?) Cohansey sand of New Jersey, however, is artesian in large part.

In evaluating the water-producing capabilities of artesian aquifers there are three aspects of primary importance, the perennial recharge, the capability of the formation to transmit that water downdip to points of discharge, and the volume of water in storage. By far the most important is the rate at which water will flow through the beds down the hydraulic gradient. The rate of replenishment is calculated as a function of water (precipitation) available on the outcrop and the rate of acceptance of that water by the aquifer. In Coastal Plain aquifers, recharge from precipitation downdip from the outcrop, either by flow westward or by downward leakage, or from flow eastward from crystalline rock areas, is not taken into account, although it is undoubtedly highly significant in many places. The capability of artesian aquifers to transmit water to points of discharge is a function of the permeability and the thickness of those sands (expressed as transmissivity), and the slope of the artesian pressure surface, that is, the hydraulic gradient or piezometric slope, from the outcrop to the point of discharge.

Theoretical maximum discharge from artesian aquifers would be achieved by lowering (pumping down) the piezometric surface everywhere to the top of the artesian bed along a line at the distance (east) from the outcrop area at which a maximum hydraulic gradient can be achieved. This distance is, of course, determined by the geometry of the geological framework. In the North Atlantic Region it ranges from 3 miles to 20 miles.

In some places the optimum distance of heavily pumped wells from the outcrop area will be less than what would be otherwise calculated owing to the nearness of the brackish water front in the aquifers.

It is of utmost importance to keep in mind that the <u>calculations of maximum available water do not take into account leakage</u>. An artesian system exists because the rocks overlying and underlying the aquifers are of low permeability. However, in any appreciably large ground-water development, the artesian pressures are lowered to a greater or lesser extent. Where those pressures fall below the pressures of water in adjacent formations, percolation through the less permeable rocks will occur. Thus, there will be an additional amount of water available to an artesian well development over and above the figures given below. However, the quality of water that might result from such "leakage" should be taken into account in any large development.

Where all aquifers are completely developed, total discharge will be limited by total recharge and in such instances leakage is canceled out as a factor. However, where development is less than total, leakage is a factor to be kept in mind. Thus, in Virginia where significant development of water in the surficial terrace formations is considered as impractical at present, potential development of artesian aquifers may be greater than calculated due to roof leakage by water from those surficial terraces. Elsewhere, areas covered by highly permeable surficial sands may be proscribed, as in the case of some of the Pine Barren country in New Jersey, now set aside as a park. These, too, may transmit large quantities of water to deeper artesian aquifers if those aquifers are developed to a maximum.

With respect to water in transit storage, it should be made clear that there are two kinds, differing enormously in quantity. Under water-table conditions, lowering the water table one foot in a sandy aquifer will release a volume of water roughly equivalent to 20 percent of the dewatered volume. However, in following recommended hydrologic procedures in an artesian system, dewatering and drainage of the formation itself will not occur because the artesian head is maintained at or above the top of the aquifer. The extremely large volume of storage, trillions of gallons, in the artesian aquifers is considered not available and is not dealt with further in this study.

When water under artesian pressure head is released from that pressure upon discharge by pumps, the volume of that water increases slightly and the aquifer skeleton contracts slightly. The coefficient of storage for artesian formations is commonly about .0002, or .02 percent. It is seen then that the water released from storage by lowering of artesian head may be 1,000 times less than the water that is released by a comparable lowering of the water level where water occurs under water-table conditions.

Although reckoned in billions of gallons this "decompression" storage water in artesian formations is quite small when compared to the volume of water moving through those aquifers from the outcrop area to heavily pumping wells and, further, it is available only once in a maximum development scheme. This type of storage water will not be considered further.

The volume of water that can be induced to flow downdip to a line of heavily pumped wells is limited by the hydraulic gradient and the transmissivity of the formation. (Possible leakage from above or below the aquifer is not estimated.) In many instances this volume is less than the potential rate of recharge at the outcrop area. Hence, some of the potential recharge at the outcrop area would be rejected and becomes overland runoff. A complex of relatively shallow, relatively low yield wells could be constructed in many outcrop areas that would capture this rejected water. The volumes available from such additional developments are also given the following discussion.

Where water-table aquifers are widely distributed and rather thick, the volume of storage is extremely high. Here, from a long term point of view, pumping is restricted to the average annual rate of recharge. However, the great volume of storage (20 percent of the volume of saturated sandy beds) remains essentially undisturbed below what can be termed the upper zone of recharge and withdrawal. This deep storage water could be drawn upon to a greater or lesser extent in drought years although in some areas there would be danger of salt water intrusion.

Where the surficial beds are thinner (south of New Jersey) development of ground water in those formations is more expensive and may consist essentially of a skimming operation by many low yield wells. Also, much less storage is available to fall back upon in times of drought. West and south of Chesapeake Bay, the coastal plain terrace formations are so thin that their development for other than small local supplies is generally impractical by conventional means.

THE ARTESIAN AQUIFERS

Nonmarine Cretaceous aquifer. The nonmarine Cretaceous aquifer system is one of the most extensive in the Coastal Plain. The thickness of individual sand beds seldom exceeds 50 feet but an aggregate thickness of 150 feet of sand for the total aquifer system is not uncommon. The aquifer system attains a thickness of 6,000 feet of fresh-water-saturated sediments (sands, silts, and clays) in Maryland, 1,200 feet in New Jersey and 1,700 feet on Long Island (fig. D-5).

Through most of the Coastal Plain this aquifer system contains saline water at depths exceeding 1,200 feet below sea level, but is saline at as little as 500 feet below sea level in northern Delaware and at somewhat shallow depths along the coastline on Long Island and parts of New Jersey.

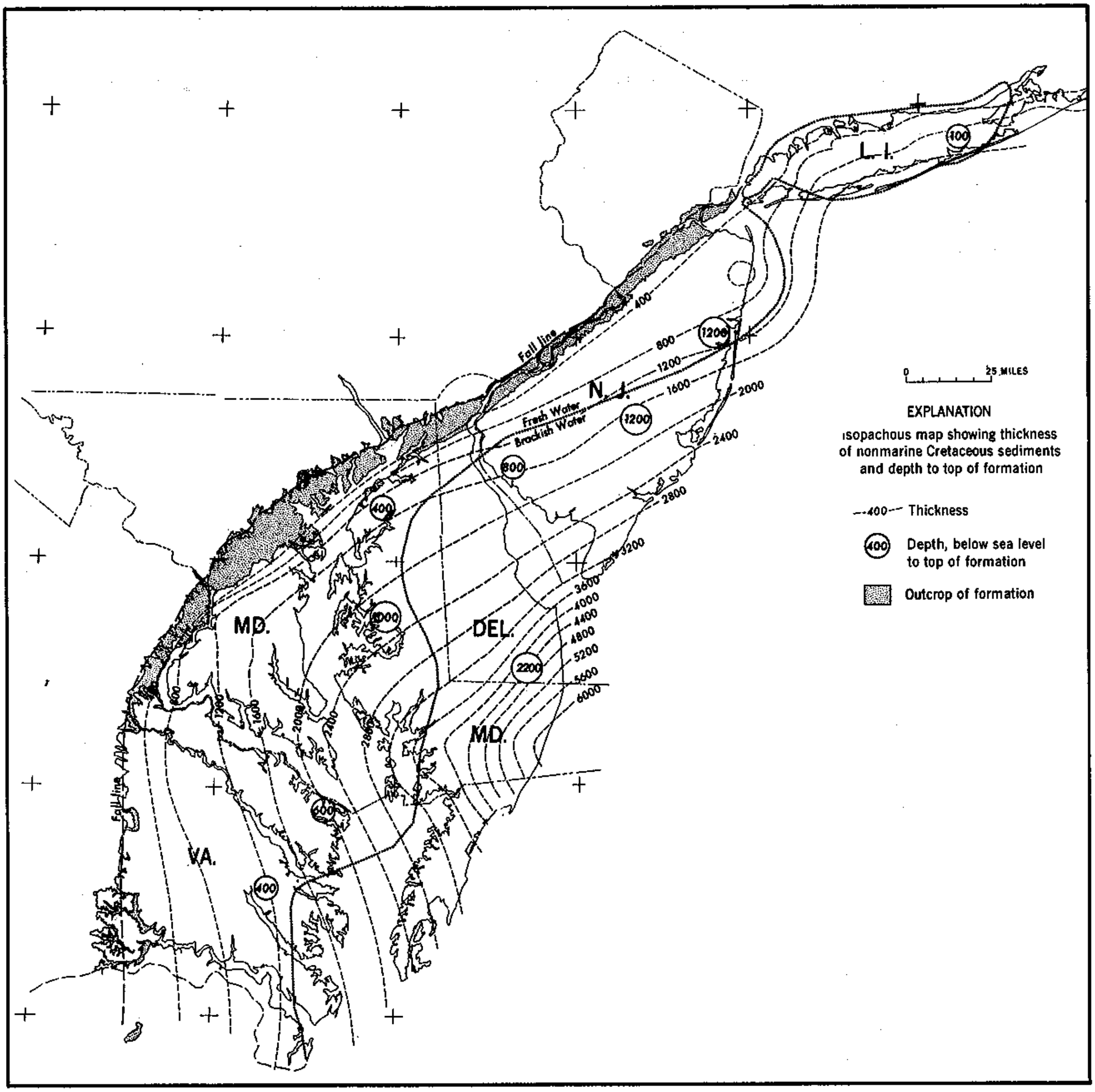


Figure D-5.--Isopachous map showing the thickness of the nonmarine Cretaceous aquifer and depth to top of the formation in feet and position of the fresh water - salt water boundary.

Estimated and determined transmissivity coefficients for the complete aquifer system 12 miles downdip (excluding the Magothy Formation in Maryland and Delaware) ranged from 24,000 gpd per ft (gallons per day per foot) in Virginia to 250,000 gpd per ft in Long Island. Transmissivity values for the Magothy Formation in Maryland and Delaware ranged from 5,000 to 75,000 gpd per ft at a distance of ten miles downdip from the outcrop.

Ignoring vertical leakage into the aquifer system, calculations based on area of outcrop, the slope of the hydraulic gradient to wells, and the transmissivity indicate (fig. D-6) that an estimated 1.080 billion gpd or 3,300 acre-ft per day (acre feet per day) could be produced from the nonmarine Cretaceous aquifer system by closely spaced wells placed in a line at an average distance of twelve miles downdip from and parallel to the outcrop. From this total an estimated 250 mgd (767 acre-ft per day) would be produced from the Long Island section, 410 mgd (1,260 acre-ft per day) from the New Jersey section, 300 mgd (920 acre-ft per day) from the Delaware-Maryland section, and 120 mgd (370 acre-ft per day) from the Virginia section.

Yields of up to $2\frac{1}{2}$ mgd may be obtained from properly located and carefully constructed wells in the Raritan and Magothy Formations in New Jersey. Yields of 3 mgd have been developed in Virginia.

Very little additional water is available from wells developed in the outcrop area where water occurs under water-table conditions. The outcrops of the nonmarine aquifer system are rather small areally and further, artesian wells downdip are calculated to be capable of producing all the water that can infiltrate those beds. In other words, development of water along the outcrop would diminish the total given for maximum artesian well production by the amount of that development.

The storage capacity of the aquifers in the artesian system is extremely large but as noted above, it cannot be utilized, particularly if the salt-water front is to be maintained in essentially its present position but under proper management much of the fresh water in storage near the outcrop could be advantageously depleted in many areas of the Coastal Plain.

<u>Englishtown aquifer</u>. The Englishtown sand is an artesian aquifer of importance in New Jersey, particularly just to the southeast of its outcrop belt. The aquifer is most widely developed by wells in Ocean and Monmouth Counties where it attains a maximum thickness of 150 feet. In southwestern New Jersey and Delaware, the aquifer is only 10 to 20 feet thick and of much lesser importance. In most of New Jersey the aquifer has an average thickness of 40 feet, three or four miles south of its outcrop. The coefficient of transmissivity for the aquifer as a whole near the outcrop averages 16,000 gpd per ft.

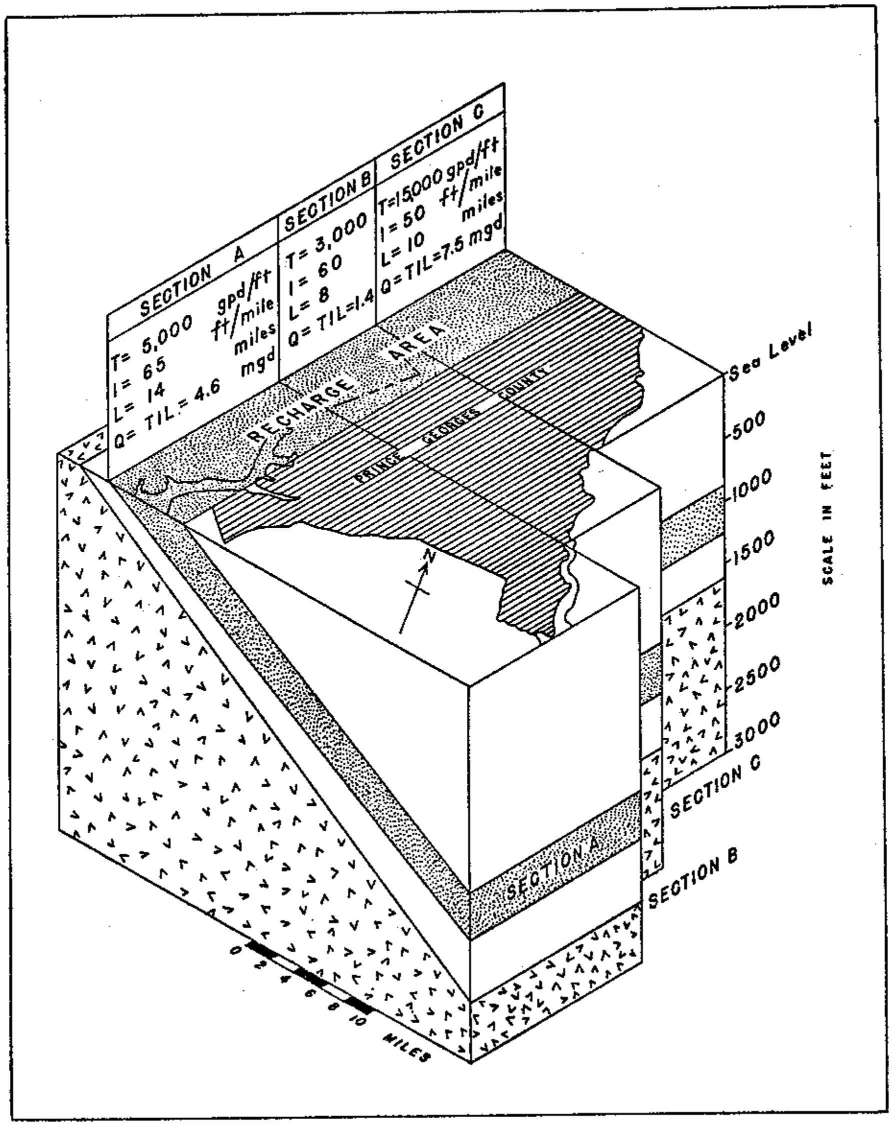


Figure D-6.--Block diagram showing the methodology employed in estimating available artesian water. The transmissivity multiplied by the hydraulic gradient and by the length of cross section gives the volume of water flowing downdip in millions of gallons a day. The gradient will be increased by lowering the water level in artesian wells by heavy pumping, but 100% of the water cannot be intercepted. Increments gained from roof leakage are not considered. Total development may be limited in places by amount of recharge in and east of the recharge area. Elsewhere recharge may be rejected. (Mack, 7)

The yield of individual wells ranges from 20 to 500 gpm (gallons per minute) and averages about 250 gpm. It is estimated that 55 mgd (170 acre-ft per day) could be produced from the aquifer from a line of closely spaced wells three miles downdip and parallel to the outcrop. With development of the water-table portion also, an additional 50 mgd (153 acre-ft per day) could be produced. This additional 50 mgd represents recharge rejected by the formation because of the relatively low transmissivity of the downdip portion of the aquifer.

Large withdrawals from storage from wells east of the artesian wells postulated would foster movement of the salt-water landward but an estimated 49 billion gallons (1.5×10^5 acre feet) of water in storage in the outcrop area might be utilized.

Wenonah-Mount Laurel-Monmouth aquifer. The aquifer system comprised of the Wenonah and Mount Laurel sands of New Jersey and sands of the Monmouth group of Delaware and Maryland ranges up to 100 feet in thickness and averages 50 feet in thickness. The sand is best developed in northeastern New Jersey. Transmissivity coefficients of 2,200 to 50,000 gpd per ft have been determined. However, a value of 12,500 gpd per ft is estimated for the full thickness of the aquifer at a distance of seven miles downdip from the outcrop.

Individual wells in these formations yield up to 750 gpm. An estimated 50 mgd (153 acre-ft per day) could be produced by a line of wells 140 miles long located seven miles downdip. An additional 95 mgd (290 acre-ft per day) of water could be produced along the outcrop area from a series of water-table wells. This additional 95 mgd represents recharge along the outcrop that would be rejected due to the relatively low transmitting capacity of the aquifer.

There are 326 billion gallons (1.0×10^6 acre-ft) of water stored in the artesian part of the aquifer and 126 billion gallons (3.9×10^5 acre-ft) of water stored in the outcrop area. Drawing appreciably upon storage in the artesian area downdip would foster movement of saline water inland.

Aquia-Rancocas-Vincentown aquifer. The Paleocene-Eocene aquifer system consists of sands of the Aquia, Rancocas, and Vincentown Formations. The sands attain a maximum thickness of 60 feet but average about 30 feet across the Coastal Plain. The sand is best developed in the Delaware to Washington area along the outcrop and downdip for 20 to 40 miles.

The coefficient of transmissivity of the aquifer ranges from an average of 8,000 gpd per ft in New Jersey and southern Virginia to an average of 22,000 gpd per ft in Maryland-Delaware area. Transmissivity values of 36,000 to 40,000 gpd per ft were determined for that segment of the aquifer in Queen Ann County, Maryland. Wells designed for large production and completed in the artesian portion of the aquifer are capable of producing up to 1,200 gpm but average 300 gpm.

It is estimated that 75 mgd (230 acre-ft per day) could be produced on a sustained basis from a line of wells placed at varying distances up to 17 miles downdip from the outcrop. Of this 32 mgd would come from the Maryland and Delaware area, 29 mgd from New Jersey, and 14 mgd from Virginia. Another 227 mgd (696 acre-ft per day) could be produced from the outcrop area by water-table wells if it were developed to its maximum potential. The greatest amount of this additional potential, 109 mgd, would come from the Maryland-Delaware sector. In the Virginia sector, 73 mgd might be produced, and in the New Jersey sector, 45 mgd.

The storage water in the outcrop area of this aquifer is estimated to be 290 billion gallons (8.9×10^5 acre-ft).

Kirkwood aquifer. The sands within the Kirkwood Formation constitute an important aquifer system under the outlying two-thirds of the New Jersey Coastal Plain. The formation is as much as 160 feet in thickness in the outcrop area but averages about 60 feet in thickness, of which 40 feet is sand. In the subsurface at Cape May, N.J., the formation has a total thickness of 780 feet, of which 190 feet is sand.

Wells designed for large production and completed in the artesian portion of the aquifer are capable of producing up to 1,200 gpm although the average yield is only about 300 gpm. The transmissivity used in estimating available water is 65,000 gpd per ft. Production from a theoretical line of wells placed 20 miles downdip and parallel to the outcrop would be 43 mgd (132 acre-ft per day). Up to 273 mgd (838 acre-ft per day) additional water could be produced from the water-table portion of the aquifer by a grid of small capacity wells.

The Kirkwood aquifer has a large amount of water in storage in the outcrop area except in Salem and Monmouth Counties, New Jersey, where the formation is very thin. Elsewhere in the outcrop area there is an estimated 425 billion gallons (1.3×10^6 acre-ft) of water stored.

THE WATER-TABLE AQUIFERS

Large areas of the Coastal Plain are blanketed by Pleistocene sands and most of the older aquifers have a sandy outcropping. In the Coastal Plain area the soil developed on sandy sediments is ideal with respect to infiltration of precipitation. Where the surface is clayey infiltration is inhibited and reject precipitation is lost as overland runoff. The greater runoff from the clay areas results in more mechanical erosion and ultimately causes the clay areas to be eroded into the sharper hill faces. The initially flat sandy areas on the other hand, tend to slope back gently away from the streams.

As estimated from soils maps and shallow well logs, the percentage of the sandy surface in the Coastal Plain ranges from 90 percent on Long Island to about 20 percent in southern Virginia. An intermediate value of 75 percent is assigned the Maryland mainland and that portion of Virginia north of Richmond.

Land elevations in the Coastal Plain are generally highest at the Fall Line and decline gradually toward the sea. Long Island, central New Jersey, and the Delmarva Peninsula have topographic highs near their central areas with gentle slopes away from the central axes. However, most of the land is about flat to rolling with numerous swamps and ponds in the flatter areas. Small streams are present throughout the Coastal Plain. The vegetation ranges from thick pine forests in Virginia to large open cultivated areas in the Delmarva Peninsula, New Jersey, and Long Island.

Water budget studies conducted on surficial (water table) formations in the Coastal Plain were examined critically. In these studies all factors of the hydrologic cycle that can be measured are measured or are closely approximated. The critical data from four such studies are given in table D-2.

As shown in table D-2 the annual rate of infiltration of precipitation to the water table ranges from about 22 to 24 inches, or over 1 mgd per square mile. Evapotranspiration from the soil zone ranges from about 16 to 21 inches. The total evapotranspiration from the water table is about 11 inches in two Coastal Plain areas but on Long Island, where the water table is commonly many tens of feet below the surface, evapotranspiration from the water table is only about one-half inch.

Discharge of water from the water table to subjacent aquifers, to streams, and to the ocean ranged from 11.86 inches in the Beaverdam Creek basin to 22.14 inches on Long Island. This is equivalent to 0.56, 0.67 and 1.05 mgd flow per square mile of

TABLE D-2.--WATER BUDGET DATA

(Figures refer to percentages and inches of total precipitation reaching the surface of the ground.)

	Surface Interception	Surface Evapor-transpi-ration	Direct Runoff	Infil-tration to Water Table	Water Table Evapor-transpi-ration	Ground Water Outflow & Underflow
Long Island N.Y., W.R.Com. Bull.#62	48.75% 21.45"	47.50% 20.90"	1.25% 0.55"	51.25% 22.55"	0.94% 0.41"	50.31% 22.14"
Delaware River Basin PP #381	46.15% 20.31"	33.17% 14.60"	12.98% 5.71"	53.85% 23.69"	22.12% 9.73"	31.73% 13.96"
Beaverdam Creek Md. WSP - 1472	48.53% 21.35"	37.17% 16.35"	11.36% 5.71"	51.47% 22.65"	24.52% 10.79"	26.95% 11.86"
Patuxent River Zones 2-3-4 HA - 244	50.00% 22.00"	36.02% 15.85"	13.98% 6.15"	50.00% 22.00"	26.14% 11.50"	23.86% 10.50"

drainage area in the budget study areas; Beverdam Creek, Md., the Delaware River basin and Long Island. The lower figures reflect the lesser amounts of sandy terrace surface in the more southerly localities. (The Patuxent River figures refer to a crystalline rock area outside the Coastal Plain.)

The vast water-table aquifer of the Coastal Plain, which includes the Cohansey Formation of New Jersey, the Upper Glacial sands of Long Island, the Pleistocene Series of Delaware and Maryland and the Columbia Group of Virginia, has an average thickness of about 90 feet. The average 90-foot section of aquifer has 16 feet of unsaturated rocks above the water table; 20 aggregate feet of clay below the water table; and 54 feet of saturated sand. The thickest sections are in Long Island, and in southeastern New Jersey to southeastern Delaware and Maryland (table D-3). In calculating the areal extent of this aquifer all areas subject to short term salt water intrusion, all areas with less than 40 percent sand thickness, and all areas too small and isolated to be economically a part of the system were excluded.

The average transmissivity value is approximately 50,000 gpd per ft but ranges from below 10,000 gpd per ft to more than 500,000 gpd per ft.

Properly constructed wells in some parts of the Cohansey are known to produce more than 2,000 gpm but only low yield wells can be developed in the more southerly part of the area.

This extensive aquifer has more usable storage capacity and outcrop area subject to easy recharge than all other Coastal Plain aquifers combined. There is an estimated 295 million acre feet of the sand reservoir containing 28 trillion gallons (86 million acre-ft) of water. If this reservoir could be drawn down fairly evenly to about 90 percent of its full capacity then all the estimated annual recharge of 3.6 billion gpd could be salvaged and used. The recharge figure given was estimated from a study of streamflow characteristics and therefore represents ground-water recharge after evapotranspiration loss. The recovery of evapotranspiration loss would raise the 3.6 billion gpd figure given to as much as 7.0 billion gpd, as explained below. The potential production from the several Coastal Plain areas (evapotranspiration salvage excluded) is given in table D-3. Where the formation is relatively thin (western Maryland and Virginia) the water produced would have to be captured by a network of shallow, very small capacity skimming wells before it migrated to the sea.

The volumes of water that might be withdrawn if all the recharge could be salvaged are 0.75 billion gpd on Long Island, 1.05 billion gpd

TABLE D-3 POTENTIAL PRODUCTION FROM THE WATER-TABLE AQUIFERS

Section	Area (sq.mi.)	Reservoir Thickness Total (feet)	Saturated Sand (feet)	Storage (gals x 10^{12})	Potential Production (Billions of gal/day)
Long Island	722 +	1/ 176	150	5.63	2/ .75
New Jersey	1883	135	90	10.34	1.05
Delmarva 3/	3071	84	50	9.12	1.02
S. Maryland	824	55	20	.87	.24
Virginia	2380	164	20	2.71	.57
	8880 (total)	91 (average)	54 (average)	28.67 (total)	3.63 (total)

1. Production from the Magothy and Lloyds aquifers is included.

2. The water budget area of Long Island considered in N.Y.W.R. Bulletin 62 is 760 square miles. King and Queens County and the North and South Forks at the eastern end of the Island are outside that budget area. The water budget figures given are 470 mgd subsurface flow, 320 mgd streamflow, 15 mgd spring flow, a total of 820 mgd, most of which is theoretically recoverable. Considering the areas outside the 760 square mile budget area either as given here by Tarver or that given in Bulletin 62, as well as the very large reuse factor of Long Island water, the figure of 750 mgd available water does not seem large. Further, pumpage in Suffolk and Nassau Counties was already 430 mgd in 1965 without bringing about notable diminuition of stream and spring flow. Raising the present pumpage to a possible 750 mgd therefore seems highly conservative to the senior author rather than otherwise.

3. Delmarva is the Delaware, Maryland, and Virginia Peninsula.

from New Jersey, 1.02 billion gpd from the Delmarva Peninsula, 0.24 billion gallons from mainland Maryland and 0.57 billion gallons from Virginia coastal plain west of Chesapeake Bay.

Direct (overland) runoff was 0.55 inches for Long Island and about 6 inches for the remainder of the Coastal Plain (table D-2). Inasmuch as direct runoff is very low, it is immediately apparent that most of the precipitation (86 to 99 percent) infiltrates the soil zone. It will be noted (table 3) that on Long Island, where the water table is generally at several tens of feet and more below the surface, evapotranspiration from the water table is negligible, and is equivalent to less than one-half inch of rainfall per year. In the areas to the south, evapotranspiration is equivalent to about 10 inches of rainfall. It follows that upon withdrawal of ground water in areas of initially high water table, the water table will be lowered and the 10 inch annual evapotranspiration loss would be reduced appreciably. Hence, potential production figures shown in table D-3 for areas south of Long Island represent perhaps as little of half of all the ground water that might be captured.

Further, it is clear that in parts of the area, including even parts of Long Island, lowering of the water table will capture some of the rejected water that is now part of direct runoff (table D-2) and to some extent may also reduce the loss of soil and surface water evapotranspiration. These gains will also tend to increase the volume of available ground water. If the water table were lowered in the areas of ponds, swamps, and scrub and trash trees in order to capture evapotranspiration loss, the ecology of the area might be disturbed somewhat but in other areas the utilization of part of the water might have little adverse effect.

The loss of water by underflow to the salt-water bodies could be salvaged by interceptor wells, trenches or other devices located near the fresh-salt water interface.

The realistic amounts of water that could be produced from each sector of the Coastal Plain would be greatly affected by the manner in which the water is used. If used locally, and if much of the water were returned to the ground, pump discharge greatly surpassing the annual recharge from precipitation might be produced. If the water were delivered and used outside the Coastal Plain, the lesser amounts shown in table D-3 could be produced because none would be returned to the ground.

PRACTICAL GROUND WATER DEVELOPMENT

In table D-4, the maximum production figures given by states have been distributed among the several basins. With a view to suggesting a conservative figure for practical development of total available water, the calculated volume of available artesian water has been reduced to two-thirds of the volumes shown in table D-3. The water in the outcrop area was reduced by half because wells there will yield smaller quantities than artesian wells and municipal and industrial consumers will tend to find other sources of supply. However, where the water table is lowered by withdrawals by wells, significant gains in salvage of evapotranspiration loss should occur and the reduced half is increased by half (e.g., 100 mgd is reduced to 50 mgd and then increased to 75 mgd). Available water in the surficial Cohansey Formation of New Jersey and in the Delmarva Peninsula (basins 15 and 18) is similarly treated. Total available water from the thin southwestern Maryland and Virginia terrace deposits (basins 18, 19, 20, and 21) is reduced to one-tenth of the figure given in table D-3 and no gain in salvage of evapotranspiration is shown. This water, available only from small yield wells, is considered to be limited to supplying rural and irrigation needs.

Water developed from artesian wells will be very inexpensive as will water from the Cohansey Formation in New Jersey. Water from artesian beds should cost less than 5 cents per thousand gallons at the well head or at one end of a well field. Development of water in large quantities from the surficial Cohansey Formation in the Delmarva Peninsula would be more expensive, up to 10 cents a thousand gallons. Water from thin surficial deposits in Maryland southwest of Chesapeake Bay and in Virginia would be much more costly to develop if more than small quantities were to be produced.

QUALITY OF GROUND WATER IN COASTAL PLAIN FORMATIONS

Artesian aquifers. Water in the nonmarine Cretaceous aquifer is principally a sodium-bicarbonate type in the Virginia area. Near the Fall Line the water is soft and low in dissolved solids but downdip the water gains in total mineral content and becomes a somewhat hard calcium-bicarbonate water (table D-5). Still further downdip the water gains still more in total mineral content but becomes a very soft sodium-bicarbonate type through base exchange. An undesirable concentration of fluoride is present in many of the high bicarbonate waters and iron is present in some waters along the Fall Zone.

From Maryland through New Jersey water from nonmarine Cretaceous beds is generally similar to that in Virginia. Along the Fall Zone undesirable concentrations of iron are present in water that is commonly acidic. Fluoride is not a problem, however.

TABLE D-4.--SUMMARY OF PRACTICAL GROUND WATER DEVELOPMENT IN THE COASTAL PLAIN.

	Municipal and Industrial (mgd)	Rural and Irrigation (mgd)
Basin 13	750	
Basin 14		
Outcrop area	24	
Artesian Beds	5	
Basin 15		
Outcrop area	45	
Artesian beds	223	
Surficial deposits	465	
Basin 16		
Artesian beds	40	
Surficial deposits	204	
Basin 18		
Outcrop area	92	
Artesian beds	91	
Surficial deposits	610	7.4
Basin 19		
Outcrop area	18	
Artesian beds	127	
Surficial deposits		24
Basin 20		
Outcrop area	23	
Artesian beds	58	
Surficial deposits		28
Basin 21		
Outcrop area	14	
Artesian beds	35	
Surficial deposits		21

As shown in figure D-3, water in the nonmarine Cretaceous aquifer is saline at differing distances downdip from the Fall Zone.

The intake area of the nonmarine Cretaceous aquifer is crossed by tidal streams in places. In New Jersey the polluted Delaware River follows the strike of the formations for a distance of 60 miles. The Potomac parallels the recharge area for a distance of 40 miles, the lower reach of which is more or less saline. Long continued heavy pumping in such critical areas may induce the intrusion of saline water or waters carrying industrial pollutants not susceptible to filtration through the sandy formation.

In Long Island the water has a very low total mineral content and very low hardness where it is uncontaminated.

Water in the Englishtown and Wenonah-Mount Laurel-Monmouth aquifers is generally a somewhat hard calcium bicarbonate type with dissolved solids ranging from 100 to 250 mg/l (milligrams per liter). In places it contains objectionable quantities of iron. Representative analyses are given in table D-5.

The water from the Aquia-Rancocas-Vincentown aquifer is a moderately mineralized calcium or sodium bicarbonate type ranging in hardness from very low to moderately high. The water is rather commonly high in iron.

Water from the Kirkwood aquifer is also a bicarbonate type, similar to that described from the Aquia-Rancocas-Vincentown aquifer. However, iron does not appear to be a troublesome constituent.

Water-table aquifers. Water from this aquifer is soft in most places, low in dissolved solids and generally slightly acidic. The pH of 8.2 shown in the sample from the 256-foot well in Nassau County, N.Y. is atypical. Objectional amounts of iron, more than 0.3 mg/l, are present in many places. High nitrate, indicating organic pollution, is somewhat common in water from dug wells.

Salt-water encroachment into the aquifer is possible where the aquifer is drawn upon heavily near the salt water shoreline. However, a very large "inland" area is susceptible to ground-water development with proper management.

SALT WATER CONTAMINATION

The artesian aquifers in the Atlantic Coastal Plain will yield very large quantities of water, as noted above. The calculations made are gross, based on generalized assumptions of intake area, permeability, and hydraulic gradient. The factor of roof leakage

TABLE D-5.---CHEMICAL ANALYSES OF GROUND WATERS FROM COASTAL PLAIN FORMATIONS.

(Constituents in milligrams per liter)

Geologic age	Early to Late Cretaceous (nonmarine aquifer)									
County State	Nassau	Nassau	Nassau	Burlington	Camden	Gloucester	Monmouth	Salem	Anne Arundel Md.	Anne Arundel Md.
Depth (feet)	762	517	256	120	86	630	481	320	24	280
Silica (SiO_2)	8.4	10	8.1	12	10	12	8.2	5.4	35	7.8
Iron (Fe)	1.1	.51	3.8	.03	2.0	.11	22	2.1	.08	29
Manganese (Mn)	- -	- -	1.8	- -	- -	- -	- -	- -	.00	.40
Calcium (Ca)	0.9	1.3	13	8	23	3	8.9	12	3.1	8.7
Magnesium (Mg)	.02	.9	1	4.4	10	1	2.5	1.4	1.6	4.4
Sodium (Na)	2.9	8.1	6.2	4.8	14	18	7.5	116	3.9	2.9
Potassium (K)	.4		2.6	1.4	10	4.6		4.9	.8	1.6
Bicarbonate (HCO_3)	3	12	51	8	88	292	12	129	1	0
Sulfate (SO_4)	5.7	7.8	8.2	14	38	6.2	13	1.8	15	42
Chloride (Cl)	3.4	3.5	4.2	8	20	19	18	131	3.2	1.8
Fluoride (F)	.0	.5	.0	.0	.2	1.6	.0	.3	.1	.2
Nitrate (NO_3)	.0	.5	.3	21	5.9	.7	.0	.0	4.2	.1
Total Dissolved Solids	24	39	73	84	203	315	66	346	41	75
Total Hardness as $CaCO_3$	2	7	37	38	99	12	32	36	14	42
pH	5.3	6.1	8.2	7.1	7.2	8.1	5.5	7.6	4.9	4.4

TABLE D-5.---CHEMICAL ANALYSES OF GROUND WATERS FROM COASTAL PLAIN FORMATIONS--continued
(Constituents in milligrams per liter)

Geologic age	Early to Late Cretaceous (nonmarine aquifer)									
County State	Kent Md.	Prince George Md.	Somerset Md.	Talbot Md.	Isle of Wight Va.	Nansemond Va.	Norfolk Va.	Prince George Va.		
Depth (feet)	168	490	1,076	1,420	600	717	720	120		
Silica (SiO_2)		12	14	89	31	51	51	31		
Iron (Fe)	2.6	83	.12	10	.02	.20	.20	.25		
Manganese (Mn)	- -	- -	- -	.28	- -	- -	- -	- -		
Calcium (Ca)		39	.5	15	.3	2.3		38		
Magnesium (Mg)		15	1.2	8	.3	.8		10		
Sodium (Na)	3.9	4.9	294	4.5	102	213	528	15		
Potassium (K)		5.5	3	5.1	4.5	6.7		19		
Bicarbonate (HCO_3)	34	203	586	36	233	518	616	222		
Sulfate (SO_4)	.8	9.2	51	57	9.5	13	65	3.3		
Chloride (Cl)	2.6	1.4	70	2	10	25	408	3		
Fluoride (F)		.1	2.2	.1	6.6	6.4	4.8	.4		
Nitrate (NO_3)	.1	.5	1.3	.2	.15	.06		1.1		
Total Dissolved Solids		184	732	124	282	549		219		
Total Hardness as $CaCO_3$	24	159	6	70	2.5	9	12	136		
pH	6.1	7.8	8.5	6.3						

TABLE D-5.--CHEMICAL ANALYSES OF GROUND WATERS FROM COASTAL PLAIN FORMATIONS--continued
(Constituents in milligrams per liter)

Geologic age	Late Cretaceous (Wenonah Fm., etc.)			(Englishtown Fm., etc.)				Paleocene-Eocene (Aquia, Rancocas, Vincentown Fm.)		
County State	Gloucester N.J.	Monmouth N.J.		Burlington N.J.	Ocean N.J.	Salem N.J.		Salem N.J.	Prince George Md.	St. Mary Md.
Depth (feet)	100	452		392	1,136	133		133	23	494
Silica (SiO_2)	18	14		9.7	12	36		36	20	10
Iron (Fe)	5.6	1.5		.02	.19	1.9		1.9	16	.17
Manganese (Mn)					.06					
Calcium (Ca)	34	28		27	5.8	60		60	6	3.6
Magnesium (Mg)	1.2	6.1		4.6	.6	8.7		8.7	1.5	1.1
Sodium (Na)	2.2	8.4		2.7	67	7.4		7.4	5.1	49
Potassium (K)	2.8			7.4	7	4.9		4.9	3.5	
Bicarbonate (HCO_3)	83	107		112	211	212		212	18	136
Sulfate (SO_4)	20	16		6.4	3.8	24		24	4.1	8.9
Chloride (Cl)	5.9	5.8		2.2	2.2	5.6		5.6	11	2.5
Fluoride (F)	.5	.1		.1	.1	.4		.4		
Nitrate (NO_3)	.2	.6		.9	1.6	.7		.7	3.7	.6
Total Dissolved Solids	133	130		118	210	254		254	67	148
Total Hardness as $CaCO_3$	90	94		86	17	186		186	22	95
pH	7.6	7.8		8	8.6	7.6		7.6	6.1	8.5

TABLE D-5.--CHEMICAL ANALYSES OF GROUND WATERS FROM COASTAL PLAIN FORMATIONS--continued
(Constituents in milligrams per liter)

Geologic age	Paleocene-Eocene			Miocene (Kirkwood Fm.)			Miocene(?)-Pleistocene (Cohansey Fm., Columbia Group)			
County State	Hanover Va.	Henrico Va.		Burlington N.J.	Kent Del.		Atlantic N.J.	Salem N.J.	New Castle Del.	
Depth (feet)	154	268		350	242		100	105	95	25
Silica (SiO_2)	8	16		26	55		6.2	22		14
Iron (Fe)	2.6	.18		.10	.13		0.2	1.5	5	.03
Manganese (Mn)					.01					
Calcium (Ca)	41	6.7		.8	48		2.	2.3	4.8	11
Magnesium (Mg)	12	2.3		.9	6.9		2.9	.4	3.9	8.1
Sodium (Na)	28	57		2.9	6.4		9	7.4	5.1	18
Potassium (K)				2.2	2.5		1	5.2		1.2
Bicarbonate (HCO_3)	210	164		1	192		2	11	4.3	20
Sulfate (SO_4)	7.7	8.1		10	2.		5.4	19	12	40
Chloride (Cl)	23	4		3.1	3.4		13	3	10.6	27
Fluoride (F)	.1	.4			.1			.2		
Nitrate (NO_3)	.1	.5		.1			15	1.2		15
Total Dissolved Solids	224	167		49	219		54	61		146
Total Hardness as $CaCO_3$	152	26		6	148		17	7	28	61
pH		8.1		4.7	7.9			6	5.6	

TABLE D-5.--CHEMICAL ANALYSES OF GROUND WATERS FROM COASTAL PLAIN FORMATIONS--continued
(Constituents in milligrams per liter)

Geologic age	Miocene(?)-Pleistocene (Cohansey Fm., Columbia Group)									
County State	Caroline Md.	Queen Anne Md.	Northum-berland Va.	Prince George Va.						
Depth (feet)	76	16	15	35						
Silica (SiO_2)	6.5	9.5	15							
Iron (Fe)	.1	.04	.02	1.5						
Manganese (Mn)		.06								
Calcium (Ca)	6.7	5.5	20							
Magnesium (Mg)	.1	4	7.8							
Sodium (Na)		10	53							
Potassium (K)		6.8								
Bicarbonate (HCO_3)		9.6	80	8						
Sulfate (SO_4)	.8	6.2	45	3						
Chloride (Cl)	33	11	54	8						
Fluoride (F)				.2						
Nitrate (NO_3)	4.8	42	2.9	1						
Total Dissolved Solids		107	82							
Total Hardness as $CaCO_3$	24	31	254	15						
pH	5.5	6								

can hardly be more than guessed at except in specific site studies where much detailed information can be assembled.

Therefore, the general estimates of the volumes of water available from Coastal Plain formations given here cannot be considered hard data on "safe yield," however that term may be defined. Hence, it would be unwise to assume that as long as pumpage is not greater than as stated in table D-4, there will be no danger of brackish water movement toward the well field.

Any large development of ground water in the Coastal Plain should be "protected" by surveillance wells. A case in point is the situation at the present time at Franklin in southeastern Virginia. At the industrial complex there, about 38 mgd is being pumped and the water level at the center of pumping has declined from 12 feet above the surface to 170 feet below the surface and a wide cone of depression has been created that reaches the North Atlantic Region in the James River Basin. Lowering the artesian head at Franklin imposes no excessive financial strain in that the cost of 200 feet of lift at 1¢ per kilowatt-hour is 9 mills per thousand gallons. What is important is whether or not the cone is stablizing at its present level and what is happening at the outer rim of the cone of depression where a reversed hydraulic gradient may be inducing a slow movement of brackish water toward the inland centers of heavy pumping (fig. D-7).

This type of situation should be guarded against wherever a Coastal Plain ground-water development imposes a heavy stress on the system. Observation wells should be constructed that will show the growth and form of the cone of depression. Wells at and up to few tens of miles from the center of pumping will indicate that an undue stress is or is not being placed on the system with respect to total discharge and that total discharge is greater or less than recharge or that a balance between the two has been reached. Surveillance wells near the outer edge of the fresh-water zone will, by periodic measurements of artesian head and by sampling of the water, show that brackish water intrusion is an actual or potential danger or is not.

Where it is found that the discharge is greater than the system can sustain for more than, say, two or three years, various measures can be taken. First, total discharge can be reduced until observation well data show that stabilization has taken place. Second, artificial recharge in the general vicinity of heavy discharge can add water to the system and thus reduce the stress and, third, a fresh-water barrier between the center of heavy pumping and the brackish or salt water front might be created, also by artificial recharge through injection wells. A fresh water barrier, if geological conditions are such that one can be created, will not only

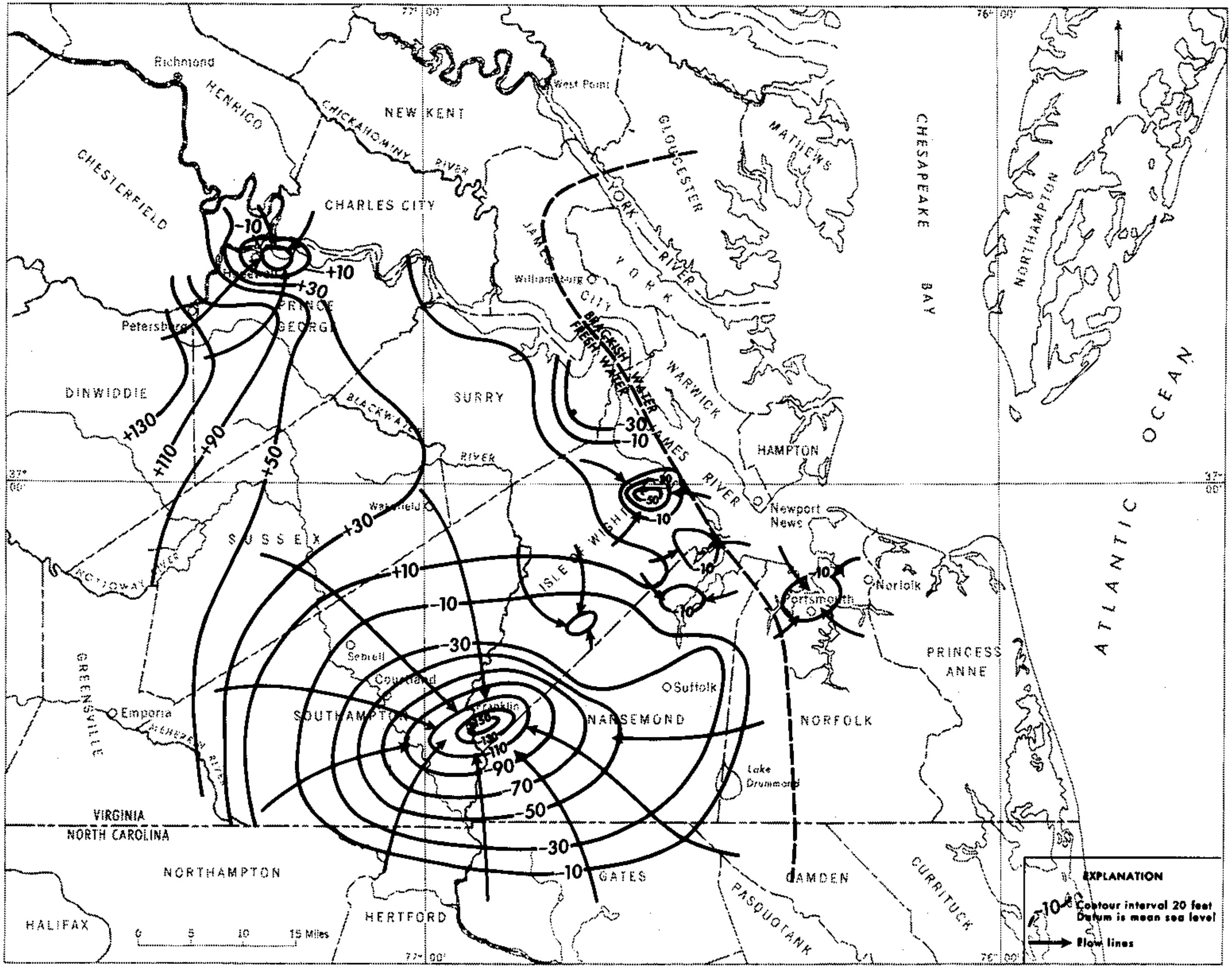


Figure D-7.--Sketch map showing cone of depression around Franklin, Va., and relation to saline water front. Cone centering at West Point at head of York River is not shown. (From Wait, R. L., 1968, Virginia Water, v. 3, no. 3, Va. Div. Water Resources) prevent encroachment of brackish water but may also permit increases in discharge in the fresh-water zone.

CHAPTER IV

GROUND WATER IN THE CONSOLIDATED ROCKS

INTRODUCTION

A part of the work package in the North Atlantic Region Water Resources study has been to evaluate the yield of wells in various geologic environments in order to determine subsequently both the quantities of ground water that might be pumped and the cost. This section of the report deals with the yields of wells in various hard rock formations. The rate of annual recharge per unit area, the underground storage capabilities of the formations and other aspects of ground-water development are dealt with elsewhere.

It is not possible to predict the yield of any one well drilled in consolidated rock formations; a well in a generally favorable aquifer may yield almost no water and a well in what is commonly known to be a poor aquifer may yield over 250 gpm. On the other hand, in a multiple well development where, say, 5 or more wells are drilled, the average yield can be predicted within reasonable limits. The chart, (fig. D-8) summarizes the various data (9) on which the study is based. The methodology utilized, the assumptions made and conclusions reached are given below.

FACTORS INFLUENCING ESTIMATES OF YIELDS

There are many factors influencing the yield of a well. Foremost is the type of rock in which the wells are developed. Where rocks are plastic, such as shales and most schists, fractures produced by earth movements will tend to close up and relatively small quantities of water are available from wells penetrating them. Fractures in brittle rocks, such as sandstone, will tend to remain open and yield more water. Rocks in which the fractures and fissures are enlarged by later solution, that is, limestones, will yield still larger amounts of water. The evaluation of yields in hard rocks is thus necessarily based on consideration of each of the different rock types in the region.

Industrial and municipal wells only are used in evaluating yields because these are the only wells where the intent has been to develop the maximum supply of water. Domestic wells and "average yields" of all wells as given in many reports are useless for purposes of evaluation. Such records represent average needs of the consumer rather than the maximum potential of the wells.

Figure D-8.--Chart (on facing page) summarizing data on which estimates of yields of deep wells in consolidated rocks are based. Bold-face numbers refer to average yield in gallons per minute. Small numbers in circles show the number of samples in the average. The light-face numbers, e.g., (395-300) 18, refer to yield, depth and drawdown of the highest yield well in the sample.

a. Greater Washington area. Two wells yielding 1,000 and 950 gpm excluded from the average.
b. One well yielding 1,515 gpm excluded from the average.
c. Well yielding 760 gpm excluded from the average.
d. Wells shallow.
e. In descending order, average yields at Providence, Bristol, and East Greenwich.
f. Many wells shallow.
g. Limy shales.
h. Shaly limestone.
i. Limestone.
j. Slaty or quartzitic rock.
k. Berkeley County, West Virginia.
l. Well in sandstone.
m. Seneca County. Some wells in Seneca and Wayne Counties yield brackish water.
n. Slaty shales, Dutchess County.
o. Taconic sequence.
p. More than half the wells are shallow.
q. Two wells yielding respectively 1,400 and 1,600 gpm excluded from the average.
r. Quartzite.
s. Shale.
t. Richmond area.
u. A well yielding 500 gpm omitted from the average.
v. A well yielding 365 gpm omitted from the average.
w. A well yielding 400 gpm omitted from the average.

	FORMATIONS \ AREAS	VIRGINIA	WESTERN MARYLAND	EASTERN MARYLAND	SOUTH-CENTRAL PENNSYLVANIA
MESOZOIC	Triassic sandstones and shales	[a] **157** (25) (600-955)151			
PALEOZOIC	Pennsylvanian sandstones with interbedded shale and coal measures		(75-250)8 (220-200)	**75** (12) (300-1276) (300flow-831)	**100** (10) (250-175)15 [d] **75?** (8) (150-120)61 **150** (31) (832-107)25
	Mississippian shale and subordinate sandstone in upper part of section and sandstone with subordinate shale in lower portion		(130flow-257)	(65-250)	(400-365)65 (100-83)15
	Upper Devonian shale, sandy shale and sandstone		(57-380)40	**25?** (44-605)	(40-300) (80-300)100 (15-260)30
	Middle Devonian shale and suborinate sandstone		(24-200)40	**25** (50-118)	
	Devonian Limestone				[g] (40-385)20
	Devonian Sandstone			(200-440)	(250-212)60
	Devonian to upper silurian massive limestone			(400-550) **85?** (170-194)	(380-313)115 (500-100)
	Silurian limy shale grading down to sandy shale and sandstone	[k l] (300-115)		(175-952)	[l] (386-496)
	Ordovician shale and minor sandstone	(50-155)29		(50-120)	(60-240)200
	Ordovician to Cambrian massive limestones	(140-801) (150-244) (300-360) (1200-260)10		**150** (16) (385-305)66 **82** (8) (370-300)150	(500-301)50 (500-365) (375-305)57
	M. Cambrian shale	(64-363)20			
	L. Cambrian limestones	(2950-960)		(300—87)	
	Lower Cambrian sandstone, shale, slate and quartzite	[j s] (45-236)'0'		**50** (6) (103-720)18	[s] (Large-300)
PRE CAMBRIAN	Granite	[t] **90** (44) (380-600)94		**50?** (4) (100-226)	
	Granite Gneiss				
	Schist	**100** (24) (275-451)2+		**100** (15) (300-140)	
	Greenstone	**20?** (3) (35-360)		**50** (9) (160-161)10	
	Marble			**100+** (12) (200-695)30	

SOUTH-EASTERN PENNSYLVANIA	NORTH-CENTRAL PENNSYLVANIA	NORTH-EASTERN PENNSYLVANIA	EASTERN NEW JERSEY	SOUTH-EASTERN NEW YORK	EASTERN NEW YORK	NORTHERN NEW YORK	WESTERN MASSACHU-SSETTS	SOUTH-EASTERN MASSACHU-SSETTS	CONNECTICUT	RHODE ISLAND	MAINE
162 (11) (395-300)18			300 (117) (870-400)73	b 192 (65) (675-252)			c 65 (16) (125-407)		157 (76) (510-600)105		
	(250-200) (150-203)20	(80-150)12 95 (15) (160-566)115						PALEOZOIC METAMORPHIC ROCKS 75 (14) (250-504)14		98+ (57) (320-500) 46 (12) (100-477) 64 (12) (150-504)	(140-151)
	150 (19) (600-237)30	110 (47) (375-600)115 (133-800)40									
	f 62 (30) (300-311) f 73 (31) (250-247)47	75 (53) (320-285) 38 (7) (89-266) 48 (8) (75-190)		150 (22) (550-140)	90? (4) (150-245)						
	(100+-153) (300-186)	110? (5) (100-335)28				(40-204)					
	g (100-108)			h (200-275)		i (300-386)					
	(400-244)50										i 150 (355-300)40
		(250-360) (185-202)									j (90-418)8
	(160-80+)	75 (11) (130-302)small 100? (12) (200-227)		m 60? (150-787)		(150-153)					
90 (33) (250-350)				n 50 (18) (135-300)	(60-160)						
(160-402) 120+ (13) (500-42)'0'				o p 55 (17) (220-228)40	(2000-361)	300? (400-416)	o q 250 (17) (803-462)				
350 (43) (1450-1020)				o j (37-220)97			o r (485-726)31				
s (225-225)											
(75-200)				f 30+ (15) (75-180)				VARIOUS AGES u 90 (18) (150-189)½			(150-85)
40 (8) (100-100)				fv 35+ (29) (80-80)					(80-122)100		
80 (31) (250-500)				w 65 (47) (280-166)61			(100-87)		(100-200)		(100-208)
				(200-600)							
(110-69)				90 (19) (300-300)							

Figure D-8.--Chart summarizing data on which estimates of yields of deep wells in consolidated rocks are based. See explanation on page D-38.

It is assumed that average yields given here are available from wells about 400 feet deep, except in shales where wells about 250 feet furnish all or nearly all the water that is available.

Not all wells selected for averaging were of the optimum depth, but correction of yields to optimum depth was not attempted in most instances.

Yields, as given, are those obtained utilizing 100 feet of drawdown. A great many of the records at hand do not show the drawdown at discharge stated. Where drawdown was given, some small adjustments to 100 feet of drawdown were made. These adjustments ordinarily made only small differences in yield estimates.'

Lastly, it is assumed that in planning based on yield figures given, production wells will be located by a hydrologist to achieve sufficient distribution of locations to encompass average conditions or to take advantage of whatever favorable conditions are recognized.

The distribution of wells in any area will greatly influence conclusions reached after study of existing records. Wells clustered in a limited area rather than randomly distributed over a wide area may lead to estimates that are too high or too low. Therefore, in selecting wells on which to base average yields, two or more closely spaced wells anywhere were averaged as one well.

A well yielding significantly more water than the group of other industrial and municipal wells in an area was omitted from the group because the one very high yield well may be in an expecially advantageous location not likely to be found in subsequent drilling. If this manipulation be considered incorrect, then figures given here for average yields are slightly low. No very low yield or "dry" wells were omitted from the group selected for averaging.

The source of recharge may influence well yields greatly. Where hard rocks are overlain by saturated sands, wells drawing water from hard rock at depth may have higher sustained yields than where such easy sources of recharge are lacking. Some high yield wells were excluded from the averaging where especially easy recharge was apparent. Hard rocks in the southern Piedmont are overlain by a more or less saturated weathered rock material (saprolite) that is a reasonably effective source of recharge. These rocks have somewhat better yields, seemingly, than wells in rock areas of New England where the saprolite has been removed by glacial action and much of the rock is covered by glacial till.

In the summation of the data from which the average yields of wells in hard rock formations were estimated (fig. D-8), considerable variation in apparent yields may be noted. Many of the apparent differences are a function of the degree of effort on the part of large water consumers to obtain a maximum volume of water from wells. For example, significant yields from wells in crystalline rocks--granite and schist--can be demonstrated only in those areas where industrial and municipal supplies were needed, as in Richmond, Va., the Washington-Baltimore area, and coastal New England. Although individual wells in limestones and dolomite are known to yield very large quantities of water almost everywhere, a high average yield for wells in these formations can be shown only where a group of a dozen or more industrial wells is the basis for evaluation, as in southeastern Pennsylvania and western Massachusetts. Industrialized northeastern Pennsylvania and southeastern New York State yield critical data on wells obtaining water from shaly beds. It is clear only in those places where many industrial wells have been drilled that wells in Triassic sandstone have high yields.

In some few instances the estimates arrived at are based on yields of wells of less than optimum depth. These wells will not produce as much as wells 400 to 500 feet deep in most formations. The difference in apparent yields between shallow and deep wells is illustrated in estimates of yields in granite. Average yields are fairly high in Virginia (Richmond area), where most of the wells considered are deep, but in southeastern New York State the 20- and 40-gpm average yields of "commercial" wells (hotels, etc., rather than industrial plants) in Putnam and Dutchess Counties reflect the fact that most of the wells are relatively shallow. In this instance much more reliance should be placed on the yields obtained from the Virginia group of wells.

The apparent low yield of wells in Upper Devonian shales in Sullivan County, less than 50 gpm as compared to 150 and 90(?) in adjacent Delaware and Greene Counties in southeastern New York, may likewise reflect the lack of industrial wells in that area, or it may be due to differences in rock types.

THE WATER-BEARING FORMATIONS

The water-bearing formations are arranged in order of their ages, the older formations being at the bottom of the chart (fig. D-8) and the younger above in ascending order. However, the group of Precambrian formations are not in chronological order and, further, any one designated rock type may include more than one formation, that is, "granite" in Virginia may include two different granites, neither of which is necessarily exactly equivalent in age to a "granite" in Pennsylvania or New England. Many New England granites are late Paleozoic in age.

The massive Cambrian to Ordovician limestone aquifer that extends from Virginia to southern New York (in the North Atlantic Region) may not be the exact age equivalent of the limestones of the Taconic sequence in easternmost New York and western Massachusetts. The exact age of the clastic sediments below the limestones of the Taconic sequence is also doubtful. Correlation of metamorphosed Paleozoic sediments in New England with specific formations in the Appalachian area is not inferred.

Precambrian rocks

Marble. Ancient carbonate rocks included in the crystalline rocks of the Piedmont Province (Plate D-1A) have a very limited distribution. A few wells in and around Baltimore and in New York City have developed high yields in marble, but data are so limited that an average yield of about 100 gpm is all that may be assigned at this time.

Greenstone. Greenstone is another Precambrian formation that has a rather limited distribution along the eastern seaboard. The formation is generally considered a poor aquifer but, on the other hand, few attempts have been made to develop greenstone as a source of water for industrial use. Therefore, its potential cannot be properly evaluated at this time. In Allegheny and Washington Counties, Maryland, where more than minimum effort was made to develop the formation, an average of 50 gpm was obtained from nine wells. Three wells in Frederick County, Maryland, yield an average of over 80 gpm with low to moderate drawdown. However, three deep wells in Fairfax County, Virginia, yield an average of only about 25 gpm. Drawdown is not known. The formation should be regarded as unreliable as a source of more than minimum supplies of water until more is known of its characteristics.

The Catoctin Formation in Virginia, although commonly referred to as "greenstone" is made up of several elements, among them arkose and conglomerate. A well at Warrenton, Virginia, that yields 550 gpm with 48 feet of drawdown, is developed in an arkosic phase of the Catoctin Formation.

Schist. Schist of various origins is somewhat widely distributed in the belt of Precambrian rocks east of the Appalachians and in New England. A true schist is a highly micaceous plastic formation in which water-transmitting fissures tend to close. However, many of the schists have been injected by or have absorbed granitic fluids and are quite brittle and tend to retain open fractures created during earth movements. Hence, most schists in this area are fairly good water-bearing formations. As seen in figure D-8 average yields of about 100 gpm have been obtained from industrial and public supply wells developed in schist in the greater Washington area and 80 gpm in the Philadelphia area. Any one well in schist may yield only 5 to 10 gpm and the average yield given above will be obtained only in a multiple well development.

It is likely that the higher yields will be obtained from wells in schist and other crystalline rocks where wells are located along fracture traces. These are generally marked by valleys. Well development in the Shetucket River basin of eastern Connecticut is not sufficient to characterize maximum potential yields of either the schists or the gneisses that make up bedrock in that area, but study of the data does show conclusively that nearly all "hilltop wells" are very poor producers and the larger yields are obtained only on the lower flanks of the mountains and in valleys on or near zones of fracture and easy recharge.

The records from Westchester County, southeastern New York, illustrate the difficulty of arriving at a representative yield for multiple wells in the schist. Sixteen wells ranging from 250 to 350 feet in depth yield an average of 86 gpm. Correction for drawdown would raise this figure slightly. However, thirty wells ranging from 350 to 830 feet in depth yield an average of only 50 gallons per minute (omitting one very high yield well that is not characteristic of the group).

It is apparent that here most of the wells that were drilled beyond 350 feet were the poor producers whereas the abundant producers were drilled only to an intermediate depth. Obviously, if the 250 to 350-foot wells were drilled deeper they would yield at least the 86 gpm noted and, in fact, possibly over 100 gpm. The shallower wells must be considered with the deeper wells in this instance in attempting to evaluate the potential yields of wells in the formation. Manipulating the data in various combinations, yields of 65, 58, or 68 gpm may be obtained. The 68 gpm yield is based on the average yield of the 16 intermediate depth wells and an equal number of average yield deep wells.

Granite gneiss. Granite gneiss, a rock that may be most conveniently thought of as a banded granite, appears to be a poor water-bearing formation. Records bearing on an intensive development of wells in gneiss are at hand only from Westchester County in southeastern New York State. There about half the wells chosen for averaging are less than 300 feet deep. Further, two public-supply wells of moderate depth, yielding respectively 365 and 250 gpm, were omitted. If these two wells represent results that may be obtained from place to place, the overall average yield is about 50 gpm rather than the 35 gpm figure given on the chart. In Putnam

County, New York, deep wells penetrating the gneiss are rare and the highest yield reported is 40 gpm at a depth of 135 feet. The data are not considered diagnostic of maximum yields available from the gneiss.

By selecting well locations in valleys that will represent fracture zones in many instances, and which will ordinarily be subject to good recharge from overlying sediments, average yields greater than 50 gpm can probably be obtained from granite gneiss in glaciated terrane.

Granite. Granite is ordinarily considered a rather poor water-bearing formation but the facts belie this notion. Many wells ending in granite have low yields. Yet, from place to place, high yields have been obtained where the wells are 400 to 450 feet deep and where a fairly large drawdown is used. The assemblage of forty-four well records in the Richmond-Petersburg area from which an average of 90 gpm was obtained includes five deep wells that are definite failures, each yielding only a very few gallons a minute, and 11 wells that are less than 250 feet deep. Records elsewhere are too few or the wells are too shallow to characterize the yields in granite elsewhere except in southeastern Massachusetts where yields comparable to those at Richmond, Virginia, were determined. In both localities, a ready source of recharge is available; in the Richmond-Petersburg area bedrock is overlapped by coastal plain sediments and in southeastern Massachusetts most wells are located on low ground with a cover of sediments of glacial origin. Where a weathered rock or other cover of somewhat permeable saturated material is absent, yields of wells ending in granite (and other crystalline rocks) will be less (table D-6, last notation).

Paleozoic sediments

Paleozoic rocks of the Ridge and Valley Province (fig. D-2) include high yield limestone aquifers and sandstone aquifers of somewhat lesser potential (plate D-1A). Paleozoic sandstone characterizes much of the Appalachian Plateau Province.

Lower Cambrian metamorphics. The potential of the more or less metamorphosed Lower Cambrian sediments, shale, slates, sandstones and quartzites cannot be estimated from data at hand. Scattered records from wells in Virginia, Maryland and southeastern Pennsylvania suggest that the sandstones and quartzites may be fairly good water-bearing formations and that the average yield of multiple wells may range between 50 to 100 gpm. The shales are almost certainly poor yielders but slaty shales and slates may be fairly productive, as discussed below under the heading "Ordovician shale and minor sandstone."

<u>Cambrian-Ordovician limestone and dolomite</u>. Only a few data are available on the yields of wells developed in the Lower Cambrian dolomite that is present from Virginia to Pennsylvania but what data are available strongly suggest that large yields can be obtained from properly located wells in these formations. As in the case of all Paleozoic carbonate rocks, it is altogether likely that wells located in fracture traces will have large to very large yields whereas those drilled in unfractured massive rock will generally have very poor yields.

From 1,500 to 2,000 feet of limy shales separate the Lower Cambrian dolomites from a great thickness of Upper Cambrian and Ordovician carbonate rocks in Virginia and southeastern Pennsylvania. Little is known of the water-bearing characteristics of the shale but it is presumed to be a very poor aquifer. On the northern rim of the Adirondacks in New York State a thick sandstone is present beneath the thick Cambro-Ordovician limestones. Little is known of its potential as a water producer. It is relatively fine grained and may not be as productive as younger sandstones in the North Atlantic Region. Older Cambrian sediments are not exposed in the northerly portion of the area except for the Taconic sequence in easternmost New York and westernmost New England. These will be dealt with below.

The thick limestones of Upper Cambrian and Ordovician age can be dealt with briefly. They are the best water producers in the area. High yields, a few in excess of 1,000 gpm, are known from many localities in the structurally deformed limestones of the Shenandoah Valley and in the Taconic Mountains of westernmost New England (fig. D-8, including footnotes) and eastern New York. Study of available records initially led to the conclusion that the average yield of wells in these limestones should be about 300 gpm.

Along the border of New York and New England a series of Cambrian and Ordovician rocks have been thrust against the more stable area to the west. These rocks make up what is known as the Taconic sequence. Within this group are thick limestones that are more or less age equivalents of the Cambro-Ordovician limestones discussed above. Due to the aforementioned structural deformation the rocks have been greatly shattered from place to place, as a result of which some very high yield wells have been developed in the formation. In western Massachusetts 17 industrial wells have an average yield of 250 gpm, excluding two wells that yield, respectively, 1,600 and 1,400 gpm. The two highest yield wells are excluded because they may represent especially favorable conditions near a major fault.

A well in Washington County, New York, yields 2,000 gpm. Drawdown is not known. The average yields of existing wells in these limestones, many of which are so located that they do not penetrate large solution channels, is about 250 gpm. On the other hand, seventeen wells in this limestone in Dutchess County, New York have a much lower average yield, about 55 gpm. The rock there may be much less shattered than in western Massachusetts. However, only 6 of the 17 commercial and small municipality wells used in the averaging are deeper than 228 feet and seemingly there has not been a general effort made to develop a maximum supply of water here. In northernmost New York the average yield of limestones may not be especially high inasmuch as the rocks there are only gently warped.

In Lehigh County, Pennsylvania, an area that lies within the Appalachian Valley system of folded and faulted rocks, the Cambrian and Ordovician carbonate rocks (10) yield from 500 to 1,800 gpm. The 1,800 gpm well is only 130 feet deep. The 3 deepest wells are around 800 feet deep and yield from 500 to 540 gpm.

In the little Saucon River valley, also in Lehigh County, Pennsylvania, the Friedensville mine has "produced" as much as 30,000 gallons of water a minute from the 400-foot level. A discharge of 13,000 gpm has been seen to issue from a 3-foot diameter hole in the shaft wall and 8,000 gpm from "several small openings." A cone of depression has extended throughout the entire surrounding limestone area, as shown in a map accompanying the report. A discharge of as much as 21,000 gpm has been sustained for several years. (About 4,000 gpm of the discharge was recirculated water.)

In the writer's opinion the enormously high-yield "well" at the Fridensville mine probably does not represent a unique hydrologic situation. At Elkton, Virginia, 5 wells located 15 feet apart yield a total of $8\frac{1}{2}$ mgd or about 6,000 gpm. The question arises as what might be the available ground water there if a large diameter shaft were driven to 400 or 500 feet and a 400-foot drawdown were utilized.

It would appear that in much of the Appalachian Valley, where structural deformation has been severe, yields of 1,000 gpm or more might be generally available if conventional wells were situated along intersections of fracture traces.

Wells developed in the shales, slates, grits, and quartzites associated with limestones of the Taconic sequence have low yields. The one industrial well that ends in quartzite in western Massachusetts does have a high yield, 485 gpm with 31 feet of drawdown, but high yields of this type may not be characteristic of quartzite in other less structurally disturbed areas.

Ordovician shale and minor sandstone. A clay shale would be expected to yield relatively small quantities of water to wells and in beds of that type the average optimum yields of wells may be in the nature of 25 to 50 gallons a minute. However, in the Appalachian area of folded rocks, some shales have become slaty and being more brittle, are more fractured and hence, better water producers. Elsewhere shale formations commonly include limy or sandy lenses which again render them better aquifers than clay shales.

Wells in the somewhat slaty shales of southeastern Pennsylvania are moderate producers. Thirty-three wells in that area, nearly all of which are deeper than 350 feet, have an average yield of 90 gpm. The two shallow wells included in the average given yield respectively 208 and 120 gpm. Nine of the deep wells in the group yield from 150 to 250 gpm and seven of the deep wells yield 20 gpm or less. The shales are sandy in Maryland and limy in Virginia. Presumably they may yield about as much in those areas as they do in southeastern Pennsylvania. Data are very meagre, however, and more cannot be said of their potential at this time.

Data are also few on industrial and municipal wells in the Ordovician in New York State. Most of the shales of this age appear to be poor producers although just southeast of the Adirondacks the shales are somewhat sandy and should be fairly productive. In Schenectady County two industrial wells each yield 150 gpm at a depth of about 200 feet. In Dutchess County most wells tap slaty shales of the Taconic sequence. The average yield of 18 deep industrial and municipal wells there is about 50 gpm.

It seems clear that wells in clay shales obtain most of the water available within 200 feet of the surface but limy shales and sandy shales may yield desirable increments of water from much greater depths.

Silurian shale and sandstone. By far the greater part of the Lower and Middle Silurian section consists of shale, limy shale and sandy shales. The limy and sandy members that are present in Pennsylvania and Maryland are moderately productive. In northeastern Pennsylvania, average yield of deep wells in somewhat sandy shale may be as much as 75 gpm. Comparable or possibly even greater yields may be obtained from wells southward into Virginia.

In New York the shales are somewhat slaty. Records of a few domestic wells in Seneca County and several industrial wells in Wayne County, both outside the North Atlantic Region, suggest that yields may also be about 75 gpm in that area.

The basal Silurian sandstone (as well as minor sandstones in the Ordovician) is relatively thin and stands out as prominent ridges above a low shaly terrane. Hence, few wells are developed in it and nothing definite can be said about its water producing capabilities. In areas of strong folding the sandstones are quartzitic and should be greatly fractured. Although possibly highly permeable in places, sources of easy recharge may be lacking and, therefore, even if high yields were obtained from wells drilled in it, it will probably be difficult to sustain those yields. Further, water levels vary greatly in the ridge-making formations. During the heavier rainfall periods water levels may be high and wells yield copiously but during drier intervals water levels decline sharply and yields of wells may greatly diminish.

<u>Upper Silurian-Middle Devonian limestones</u>. The limestones in this unit may be as prolific as the Cambro-Ordovician limestones but their exposures are limited and they have not been developed by many industrial wells. Yields up to 400 gpm have been reported from individual wells in south-central Pennsylvania and eastern Maryland from Lower Devonian limestones but the Middle Devonian limestone which appears to be an excellent aquifer in New York State grades southward to limy shale in Pennsylvania where it is clearly a less productive formation. Data on wells in the Upper Silurian limestone are meagre but do suggest that the formation may be highly productive.

In the Appalachian area a thin but prominent sandstone bed (the Oriskany sandstone) separates the Middle Devonian shaly limestone from the underlying Lower Devonian to Upper Silurian limestone. In Pennsylvania and eastern Maryland excellent yields have been developed from a few wells in this sandstone formation; one well in Pennsylvania yields 400 gpm with 50 feet of drawdown and another 250 gpm with 60 feet of drawdown. Both wells are less than 250 feet deep. The formation may best be thought of as offering some "interesting" possibilities where a source of easy recharge seems likely.

The Silurian limestone present in a small area in northeastern Maine may be as good aquifers as some limestones in the Appalachian area. The average discharge of 28 wells, presumed to be industrial wells, is 130 gpm. Correcting for drawdown, the average yield is 150 gpm. However, in this average four wells are omitted because they have very little drawdown and adjustment of their yield to 100 feet of drawdown might be much too high or much too low. Two of them yield 40 gpm with 2 feet of drawdown, one yields 150 gpm with 7 feet of drawdown and one yields 100 gpm with only 1 foot of drawdown. Adjusting the yields of these 4 wells to 100 feet of drawdown seemed particularly hazardous.

The highest yield from a well in these limestones in Maine is 335 gpm with 40 feet of drawdown. This well is considered to yield 460 gpm at 100 feet of drawdown. The poorest well yields 4 gpm at a depth of 768 feet with 180 feet of drawdown.

The conclusion reached is that multiple wells in this aquifer should average more than 150 gpm.

Devonian "shales". The Middle and Upper Devonian shales show the influence of an ancient rising land mass east of New York State. The sediments in New York and southward into Pennsylvania vary in their makeup relative to the distance from that land mass. Near the land mass sediments are sandy but at some distance south the formation becomes a true shale. These sandstone and shale beds make up what is known as the Catskill delta. In eastern New York and in easterly parts of Pennsylvania, thick sandstone beds may predominate but more to the west and south the formations are essentially sandy shales and shales.

In Maryland and Virginia the Middle and Devonian shales are seemingly poor aquifers but some unexpectedly high yields have been obtained in Pennsylvania and southeastern New York State from Upper Devonian beds. Average yields of groups of industrial and municipal wells in the so-called shales range from 60 gpm in north-central Pennsylvania to 150 gpm in Delaware County, New York (fig. D-9). Lower apparent yields in northeastern Pennsylvania are based on too few records to be reliable. The higher yields, of course, reflect the presence of dominant sandstone elements in what is frequently thought of as a shaly section and, quite possibly, especially favorable recharge conditions.

Mississippian and Pennsylvanian formations. The Mississippian and Pennsylvania formations are largely sandstones with some interbedded shales and occasional limy or coal beds. A yield of 600 gpm with 30 feet of drawdown was obtained from Mississippian sandstone in one locality in Pennsylvania and 832 gpm with 25 feet of drawdown was developed at another locality from Pennsylvanian sandstones.

The highest average yield that can be demonstrated from the records of industrial wells in sandstone, 150 gpm, is from the lowest Mississippian sandstones. This figure is based on the records of 19 wells after making empirical corrections for drawdown on 13 wells in that group.

In this area, north-central Pennsylvania, there are also 15 industrial wells located along alluvium-filled rivers that were excluded in the 150-gpm average stated above. The average yield of the excluded wells is 460 gpm, without drawdown correction. With drawdown correction, the average yield of these wells is estimated to be at least 550 gpm. The wells range in depth from 141 to 266 feet in depth. It is unlikely that yields of this magnitude can be obtained except along rivers where ample recharge is available. The occurrence cited illustrates the great difficulty in assigning average yields to any consolidated rock formation. In considering both limestone and sandstone, the source of recharge is of considerable importance. Limestones probably have the more far-reaching channels to draw upon storage and recharge but where either formation is bracketed by tight shales, for example, the average sustained yield may be quite moderate.

The Mississippian and Pennsylvanian sandstones are commonly ridge-forming in the belt of folded rocks and, like older sandstones mentioned previously, the water level in these beds varies considerably from season to season with consequent effect upon well discharges. A well in the Pennsylvanian sandstone in northeastern Pennsylvania is reported to yield 250 gpm with 10 feet of drawdown in the wetter season but only 150 gpm with 133 feet of drawdown in the driest part of the year.

Where these sandstones lie in the Plateau Province to the west of the folded Appalachians, and somewhat distant from deeply entrenched streams, very much less marked variations in yield would be expected from season to season.

Acid ground waters are uncommon, even in the sandstones that include coal beds. Acid water is produced by the oxidation of sulfide minerals associated with coal but where these minerals are well below static level, oxidation occurs slowly, if at all. However, water from some wells in sandstone does have a high iron content.

By far the greater number of wells in industrialized areas of Rhode Island appear to be developed in a group of Late Paleozoic (Carboniferous) and Devonian metamorphic rocks--slate, phyllite, conglomerate and some other rock types. A few of the Rhode Island wells may be finished in intrusive (granitic) rocks. In southeastern Massachusetts a fairly accurate separation was made of wells developed in granitic rocks from those in metamorphic rocks.

The average yield of 50 wells deeper than 350 feet in the Providence area is 84 gpm. However, there are 22 shallower wells (200 to 350 feet deep) whose average yield is about 100 gpm. Clearly, the group of deeper wells includes all wells of low yield that were drilled to considerable depth in an attempt to develop more water. Seven wells in the group of shallow wells have yields greater than 84 gpm. If these are added to the group of deep wells as "compensation" for the 15 low yield wells in the deeper whose yield is 25 gpm or less, the average yield becomes about 98 gpm.

It is clear that such manipulations of data are only steps in the right direction rather than a method of obtaining an absolute "answer."

It is believed that 90 gpm is a conservative estimate of average yield to be expected in the area.

In Bristol and East Greenwich, Rhode Island, the apparent yields in the same general physical situation are much lower. The writer believes that little importance, if any, should be given those data, based on a dozen wells in each area, in the light of much better data at Providence.

The estimate arrived at for wells in southeastern Massachusetts, 75 gpm, is not greatly lower than what the Providence data indicate even though the records of only 14 wells were available for averaging, and seven of the wells in the group range from 105 to 210 feet in depth. One of the wells yields 250 gpm with 14 feet of drawdown, but adjustment to 100 feet of drawdown was not made.

Mesozoic Sediments

Triassic. Triassic sandstone, shale, and conglomerate and intercalated volcanic basalt are present as a somewhat narrow discontinuous strip extending from southern New England through Virginia (plate D-1A). Moderately high yields have been obtained from deep wells in areas that have been highly industrialized--central Connecticut, Rockland County in southeastern New York, eastern New Jersey and Pennsylvania.

The greater part of the formation is made up of sandstone and shale. In Pennsylvania and New Jersey these two members are mapped separately. The figures given for yields in Pennsylvania are averages obtained for wells drilled in the sandstone. Comparable yields in Rockland County, N.Y., central Connecticut and Virginia are from undifferentiated Triassic sediments.

The yields of deep wells in the Triassic lowland of Massachusetts, 75 gpm, contrast sharply with results obtained in adjacent Connecticut, 157 gpm. In part, the difference can be explained by the fact that there are fewer industrial wells in the former area. It should also be noted that, following the general rule adopted here, one well in the Massachusetts group that yields 760 gpm has been omitted from the final estimate. If this yield were included, the average there would be 110 gpm. The next highest yield in this small group of industrial wells is 125 gpm.

Half of the wells in the Massachusetts group are in shale, which is considered to be a much poorer aquifer than sandstone. However, some of the higher yields are reported from the wells in shale and the differences in lithology do not seem to offer further explanation of the apparent low yields in this area. It seems likely that the section in such instances is sandy shale rather than shale.

The average yield shown for wells in the Triassic in southeastern Pennsylvania, 160 gpm, is that determined from the detailed study of records from Montgomery and Berks Counties. A 740 gpm well was omitted from the group of 111 wells on which the average was based. The next highest yield of any well here is 395 gpm. In Bucks County 25 wells have an average yield of 170 gpm. The highest yield of any well in that group is 440 gpm. In Lancaster County the average yield of eight industrial wells is also 170 gpm.

In southern Pennsylvania 9 deep wells ending in sandstone in Adams and York Counties have an average yield of only 23 gpm, whereas 16 wells of intermediate depth have an average yield of 74 gpm. Here, obviously, only the poorer wells have been drilled to maximum depth. the average of all these wells is 56 gpm. If all the wells were drilled to a depth of 450 feet, the average yield would be higher but perhaps not as much as 150 gpm.

Two exceptionally high yield wells in Leesburg, Virginia, end in a limestone conglomerate. Presumably, this type of rock may be more favorable than the noncalcareous conglomerates.

In northeastern New Jersey, a few deep wells penetrating diabase flows have excellent yields (35). Here it is suggested that warping of the flows has broken up the massive rock to the extent of creating a fairly good aquifer.

In Union County in eastern New Jersey (12), the average of a group of 117 wells is above 300 gpm. The highest yield obtained from any one well is 870 gpm with 73 feet of drawdown. The high average yield here is ascribed to the presence of thick overlying glacial sediments that provide rapid recharge.

In Rockland County, New York, there are 10 wells ending in sandstone that yield more than 300 gpm. The highest yield reported from this group of wells is an almost incredible 1,515 gpm. (The location of this well is shown by the filled circle near the northern end of the belt of Triassic rocks on plate D-9.) At the well site 51 feet of sand and gravel that overlies the consolidated rock is cased off. Here, also, high yields are sustained by rapid recharge from the overlying saturated material.

Very high yields from several wells ending in sandstone, up to 900 gpm, in Mercer County, New Jersey (northwest and north of Trenton on plate D-9) are ascribed, in part, to the high potential recharge from nearby streams as well as to recharge from overlying stratified glacial drift (36).

In places in Pennsylvania and Virginia, yields of certain wells in the Triassic have declined over a period of years. There are perhaps a dozen such reports. The permeability of the formation as a whole may be such that initially high yields cannot be sustained. However, diminution of yield may possibly be due to swelling of shaly beds in the formation, perhaps because water of a different chemical character from that originally present was drawn into the formation upon continuous heavy discharge. Clogging by iron or limy deposits could also bring about a diminution of yield.

Scrubbing the walls of the well with a wire brush and surging may improve such wells if the clogging is confined to the walls of the hole. If swelling or clogging is elsewhere, it seems unlikely that the well can be brought back to its former productivity.

SPECIAL STRUCTURAL SITUATIONS

It has been brought out previously that areas of strong faulting should commonly be favorable sites for wells. In such areas brittle rocks are more or less shattered and yields of wells penetrating them may be much higher than elsewhere. Where shale and plastic schists are involved, yields may not be much greater than in areas that have not been subjected to faulting. On and along a fault water may be transmitted along the fault plane as well as through the adjacent shattered rock wells. However, as noted, gouge, crushed rock flour, may be present along the fault plane and inhibit movement of water. Under not-unusual circumstances, gouge may act as a more or less effective ground-water dam. As in the case of the well at Beacon, New York, gouge may be granulated material that is difficult to stabilize in a well penetrating it.

However, in seeking optimum well sites, it will probably be worthwhile to locate wells along fault zones in preference to other possible sites. This suggestion applies to minor faults as well as to the fewer major faults.

In western Massachusetts and southeastern New York high-yield wells are located in the Taconic overthrust area.

The 740 gpm well in Berks County, Pennsylvania, mentioned above, is situated along the Triassic boundary fault that is shown in figure D-9. In Leesburg, Virginia, a well of exceptionally high yield, 950 gpm, is located about two-tenths of a mile east of the Triassic border fault. However, this high-yield well is believed to be developed in a calcareous conglomerate. An exceptionally poor well passes through the border fault itself. Minor faults mark the Dulles Airport area where a well yielding 1,000 gpm was completed. A fairly high yield well at Culpeper lies along the Triassic border fault.

The zone of disturbed rock at the western foot of the Blue Ridge overthrust, also shown in figure D-9, is a favorable site for high-yield wells. Large volumes of ground water have been developed at Elkton, Grottoes, Waynesboro and Roanoke. At Elkton 5 wells in limestone located 15 feet apart are reported by the plant manager to yield a total of $8\frac{1}{2}$ mgd when pumped simultaneously.

In the New River Basin of Virginia (11), just south of the Shenandoah Valley, high yield wells are present in the central and western most part of the Valley. These wells are located near major faults. High yield wells are also known in those parts of West Virginia, Maryland and Pennsylvania that lie within the belt of folded rocks characterizing the Appalachian Valley and the foot of the Alleghenies. Many of the high yield wells (several of which exceed the average yield given in table D-6) are in sandstone or in slivers of carbonate rocks that are shown only on highly detailed geologic maps.

Whether or not high yields characteristic of wells in the zone at the base of the Blue Ridge can be developed in many other parts of the folded Appalachians remains to be seen. The geological framework and somewhat meagre records of wells suggest that along the major faults--and in many instances along minor faults--higher than average yields (as here defined) can be developed.

It seems likely that in the folded Appalachians development of high yield wells will require a greater understanding of structural detail than may be necessary in some other geological provinces. As an example, where low angle thrust sheets are present (13), what may the eastward projection of the thrust planes signify insofar as ground-water hydrology is concerned?

In almost any of the hard rock areas in the North Atlantic Region, high-angle faults (in the Piedmont province as well as in the folded Appalachians) will be marked by linear topographic depressions. Where the geologic framework is obscure due to lack of detailed mapping or to heavy overburden, locating wells in prominent linear depressions will improve the chances of encountering such fault zones as may be present. Valleys may also mark zones of minor fissuring that are more favorable than elsewhere.

Little attention has been paid to the desirability of locating wells on anticlinal crests. Ordinarily an anticlinal crest is the

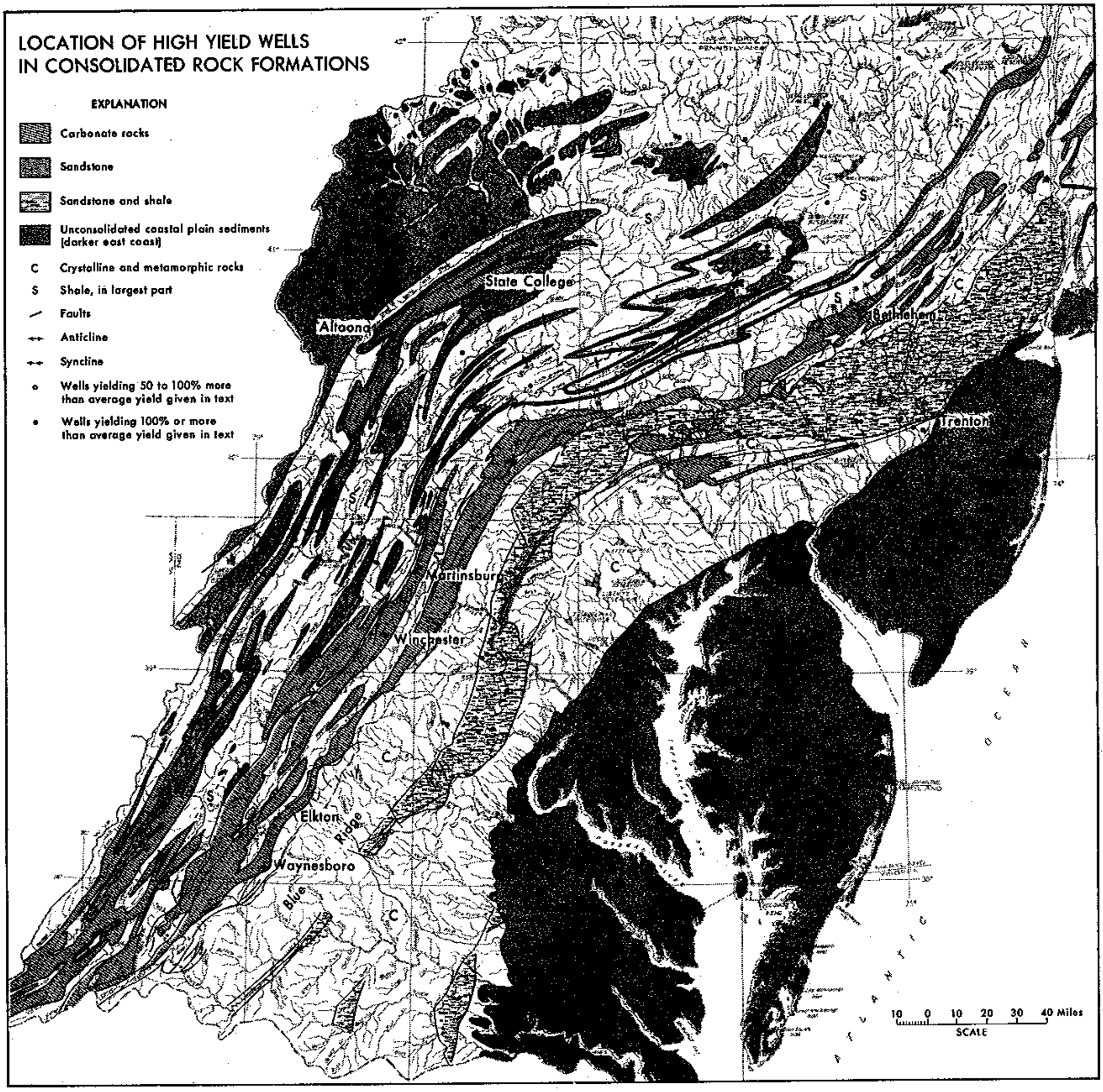


Figure D-9.--Map showing relationship of high-yield wells to geologic structure. Enlarged copy of this map is in envelope at end of book.

locus of tension cracks. In Stephens City, Virginia, 2,500 gpm is pumped from a limestone quarry. Water was tapped on the crest of an anticline but no further inflow was found as excavation proceeded down the limbs of the structure.

Synclinal troughs might be better locations for wells than elsewhere in that water will tend to be funneled into them. However, rocks in synclines may be more compressed than in anticlines where upward relief during folding has produced more fractures. In some synclinal troughs in Pennsylvania, deep wells yield somewhat highly mineralized water due to poor circulation in that zone.

Wyrick (14) has shown that in the gently tilted Plateau Province, many rock types comparable to those discussed above have very low yields. It is questionable whether yields considerably higher than the average yields given here can be developed in the less structurally deformed limestones and sandstones of northern New York State or even in those in the central and southern part of that state.

SUMMARY

It is clear that absolute values for yields of wells in consolidated rocks cannot be given for several reasons; data on which to base estimates are far from complete, the intensity of folding and faulting (roughly an index of fracturing of the rock) varies considerably from place to place, the physical character of the rocks themselves are rarely constant, and the opportunities for recharge of the formations ranges from very poor to optimum.

Nevertheless, it is necessary to adopt firm figures for planning purposes. The figures given below are those characteristic of results obtained where enough industrial and municipal wells have been drilled to give a meaningful average.

In some instances, the results reflect drilling in slightly better than average locations; as noted above the wells in granite in Massachusetts and in the Richmond, Virginia area may be more favorably located with respect to recharge than might be possible in some other areas. On the other hand, the yields for wells in limestones as given below may be very low in that the wells used in the estimates are not located on fracture traces except by chance. The figures do not reflect results possible in strongly faulted areas or some areas where recharge potential is especially favorable.

Nature has not provided neat homogeneous units of rock with characteristics that are constant even for short distances. Hence, the figures presented below (table D-6) must be accepted as being only "reasonable" and with the expectation that some variations from those figures will be met with in water developments in any one locality. However, it is thought that a 25 percent latitude will suffice for most variations above or below the figures given. With improvement in the understanding of the occurrence of ground water in consolidated rock formations, some of the average yields given may readily enough be doubled or trebled in the future.

TABLE D-6

ESTIMATED AVERAGE YIELDS OF WELLS 350 TO 450 FEET DEEP IN CONSOLIDATED FORMATIONS IN MULTIPLE-WELL DEVELOPMENTS AT 100 FEET OF DRAWDOWN

Formation	Yield, in gpm
Limestone	300
Sandstone, northern New York	100(?)
Sandstone, except northern New York	160
Shaly sandstone or sandy shale	100
Shale[1/]	40
Slaty shale	75
Limy shale	75
Granite	90
Granite gneiss	50
Schist	90
Greenstone	25(?)
Marble	100
Undifferentiated granite and metamorphic rocks, coastal New England and non-glaciated areas	90
Undifferentiated granite and metamorphic rocks, inland New England and New York	50(?)

1. Wells in shale yield little or no additional water below a depth of about 250 feet.

AVERAGE YIELD AND THE DEVELOPER

Considerable effort was made in the preparation of the section dealing with average yield of wells in consolidated rocks with the intent of providing meaningful values. The average yields presented are considered to be of the correct order of magnitude for use in a broad planning study.

Just what is an "average yield" as developed in this study? An average yield is not an absolute number. Rather it is a representation of a point midway in a group of values both higher and lower than the "average" number. In physical terms it represents, from the point of view of geology and hydrology, the average yield of wells that are scattered indiscriminately across the study areas. Where the average yield is given as 150 gpm, real yields might range from 10 to 350 gpm.

Accepting the fact that average yield is a derivation of a range of values, should a developer be content, if in a test drilling program, the well yields in carbonate rocks and sandstone do average out much as the average yield given for the formation? As discussed in the section of this report on costs, it seems likely that the developer should not be content with "average" success. Where it can be established that yields of some wells in the aquifer being considered range significantly higher than the average yield, as given in Table D-6, it may generally be worthwhile from a cost point of view to abandon at least the lower-than-average-yield wells and drill additional holes with the reasonable expectation of significantly improving the overall average of wells completed for production use. The optimum direction of a development program therefore requires a neat balancing of <u>all</u> elements involved--groundwater geology, and costs of test holes, production wells and pipeline, as well as an appreciation of political or other constraints.

Additional drilling in a haphazard manner may do little to improve the average yield of the wells initially drilled. For instance, 4 wells drilled over a period of 50 years in a community in Pennsylvania failed to improve the water supply problem there inasmuch as all 4 wells were drilled in the immediate vicinity of the town water tank. With the advice of a hydrologist, sites can be selected that appear to be the more favorable from the point of view of rock structure and sources of recharge. By so doing, there is reasonable chance that higher-than-average yield wells for production can be substituted for lower-than-average yield test wells.

It will be found that total costs in completing two or three higher yield wells rather than four or five lower yield wells may be distinctly advantageous despite the cost of drilling a total of, say, eight or ten wells. However, possible extra costs of transmission line, land acquisition, etc., must also be taken into account in evaluating alternatives.

The reader is referred to the discussion of capital costs and costs per thousand gallons of water where one or more of 10 test wells in a drilling project are found successful, as given later in this report. In that discussion it is shown that the cost of test wells is a relatively minor cost, if, sooner or later, one or more production wells is gained. If it is assumed that the successful wells were of higher-than-average yield rather than of average yield, as used in the example given, the cost elements would be proportionately more favorable than shown.

QUANTITIES OF WATER AVAILABLE FROM CONSOLIDATED ROCKS

Table D-7 shows the estimated quantities of ground water available from consolidated rocks in the various basins. It must be borne in mind that development of quantities shown may subtract substantial quantities of water from total available surface water. The subtractive effect will be reduced where evapotranspiration loss is salvaged, where water is returned to the system after use and where the enormous storage potential of the aquifers is intelligently utilized.

Hard rock wells are commonly widely distributed rather than being concentrated near large streams and rivers. Therefore, it may be assumed that they will draw upon ground storage to an appreciable extent during the low flow months. Perhaps 20 percent of the water pumped from wells in consolidated rocks might be considered an addition to the total available supply as determined by the critical low flow.

Crystalline and metamorphic rocks, shown as being only capable of supplying water for rural and irrigation needs, are actually drawn upon for small industrial supplies in a great many places and will continue to be drawn upon for this purpose in the future. Lastly, the large quantities of water shown to be available for municipal and industrial use in some basins are aggregate quantities. Full development of these quantities at reasonable cost is possible only where the demand is fairly well scattered throughout the area of sandstone and limestone aquifers.

Estimates of recharge based on annual hydrograph separation curves have been made in relatively few places. In the Maryland Piedmont, recharge was calculated at 0.4 mgd/sq.mi. in Howard and Morgan Counties and 0.6 mgd/sq.mi. in Baltimore and Harford Counties. These figures represent, respectively, 66 percent and 62 percent of the total streamflow. The recharge figures, however,

TABLE D-7

SUMMARY OF PRACTICAL GROUND WATER DEVELOPMENT
IN CONSOLIDATED ROCK AREAS

	Area (sq.mi.)	Total Recharge (mgd)	Recoverable M&I* (mgd)	Recoverable Rural** (mgd)
Basin 1	7,130			
Limestone	620	310	230	
Crystalline rocks	6,510	1,627		325
Basin 2	7,860			
Crystalline rocks	7,860	1,965		393
Basin 3	5,540			
Crystalline rocks	5,540	1,385		277
Basin 4	3,200			
Crystalline rocks	3,200	800		160
Basin 5	5,420			
Crystalline rocks	5,420	1,355		271
Basin 6	3,860			
Crystalline rocks	3,860	915		183
Basin 7	4,800			
Crystalline rocks	4,800	1,200		240
Basin 8	10,900			
Sandstone	1,100	366	275	
Crystalline rocks	9,255	2,314		463
Basin 9	4,120			
Crystalline rocks	3,870	1,290		558
Sand	250	250		200
Basin 10	4,380			
Limestone	415	138	69	
Sandstone	175	58	44	
Crystalline	4,380	1,095		219
Basin 11	11,400			
Limestone	475	158	119	
Limestone (Taconic)	750	250	125	
Sandstone	990	330	248	
Crystalline rocks	9,860	2,465		493
Basin 12	12,830			
Limestone (Taconic)	260	87	65	
Limestone	990	330	248	
Sandstone	15	5	3	
Crystalline rocks and shale	11,225	2,806		561

TABLE D-7

SUMMARY OF PRACTICAL GROUND WATER DEVELOPMENT IN CONSOLIDATED ROCK AREAS--continued

	Area (sq.mi.)	Total Recharge (mgd)	Recoverable M&I* (mgd)	Recoverable Rural** (mgd)
Basin 14	2,300			
Sandstone	1,145	572	429	
Crystalline rocks	700	233		47
Basin 15	12,440			
Limestone	505	252	189	
Sandstone	1,320	660	495	
Shale and crystalline rocks	7,725	1,931		386
Basin 16	2,190			
None				
Basin 17	27,200			
Limestone	185	62	46	
Limestone	1,330	665	499	
Sandstone (Plateau)	3,500	1,750	875	
Sandstone	3,135	1,567	1,175	
Shale and crystalline rocks	19,870	4,967		993
Basin 18	7,000			
Crystalline rocks	1,200	400		80
Basin 19	14,500			
Limestone	2,150	1,020	765	
Limestone and sandstone	970	485	364	
Sandstone (Plateau)	450	225	112	
Sandstone (Piedmont)	950	475	356	
Crystalline	1,750	583		117
Shale	7,170	1,792		397
Basin 20	5,850			
Sandstone	260	130	98	
Crystalline rocks	2,550	850		170
Basin 21	10,400			
Limestone	1,950	875	656	
Sandstone	270	135	101	
Crystalline rocks	4,350	1,437		289
Shale	1,600	400		80

* Municipal and industrial.
** Rural and irrigation.

do not include the quantities lost by evapotranspiration--that is, the figures represent only the ground water reaching the stream rather than the total amount that reached the zone of saturation. In the Piedmont of Pennsylvania, a study of Brandywine Creek showed that total recharge was 1.1 mgd/sq.mi. of which 0.83 mgd/sq.mi. reached the stream. This latter figure represented two-thirds of the total flow. In the Pomperaug Valley of Connecticut, an area of crystalline and sandstone rocks covered in part by glacial drift, both stratified and unstratified, total recharge was calculated to be 0.74 mgd, of which 0.43 mgd reached the stream. This latter figure was about 45 percent of the total streamflow.

In the Shetucket Basin of Connecticut, a crystalline rock submountainous terrain, ground-water outflow was calculated to be 0.4 mgd/sq.mi. where the rock cover is till rather than stratified sediment (15).

The recharge figures used in this report are 1/2 mgd/sq.mi. for limestone and sandstone south of the glaciated area and 1/3 mgd/sq.mi. in the glaciated region where those rocks are overlain by glacial till. Most crystalline rock areas form gentle rolling ground in the southern states and are overlain by a thick weathered rock mantle but form mountainous to submountainous areas in the northern states and generally have a cover of poorly permeable till. Hence, the recharge rate in the northern states is taken to be 1/4 mgd/sq.mi. and 1/3 mgd/sq.mi. in the southern states. The Blue Ridge crystalline rock area is considered to have a recharge rate of 1/4 mgd/sq.mi., as do shaly rock terranes.

The estimates for recharge are considered to be conservative in the light of the budget data discussed above which range from a little less than 1/2 to more than 3/4 mgd/sq.mi., exclusive of evapotranspiration loss.

It is assumed that three-fourths of the estimated recharge to limestone and sandstone terrains is available to wells except in the submountainous Taconic Mountains and in the Appalachian Plateau where only half the recharge to the limestone and sandstone strata is considered recoverable. One-fifth the estimated recharge to crystalline rocks and shales is assumed to be recoverable by domestic and low yield irrigation wells.

Ground water from wells in limestone aquifers should cost from 2 to 6 cents per thousand gallons and from 3 to 7 cents per thousand gallons from wells in sandstone where about 5 mgd is developed. In most crystalline rock areas a group of 14 wells can provide 1 mgd at a cost of about 9 cents a thousand gallons. Cost figures cited include drilling, pump and appurtenances, pipe connecting the wells, land, maintenance, amortization and power.

QUALITY OF GROUND WATER IN CONSOLIDATED ROCKS

In the following paragraphs the salient chemical characteristics of waters from wells ending in the various consolidated rock formations are summarized. About 280 analyses that seemed to typify the waters in the various formations were culled from several thousand published analyses. From this group 91 analyses were selected that show the general range of chemical quality that should be expected of water from those formations.

Most ground waters from consolidated rocks in the North Atlantic Region have a total dissolved solids content of less than 500 mg/l and a few have less than 100 mg/l. From that point of view they are considered of good quality for domestic purposes.

As a group the waters from consolidated rocks range from soft (less than 60 mg/l total hardness) to very hard (more than 180 mg/l). A few are excessively hard. Hardness is most commonly present as bicarbonate (temporary) hardness.

Most of the hard waters are from wells in the carbonate rocks. Those rocks--Cambrian, Ordovician and Devonian limestones and dolomites--are important aquifers in the folded Appalachians and in central New York. The Silurian carbonate rocks of northeastern Pennsylvania are gypsiferous. Where solution of gypsum occurs, hardness may be present in large part as calcium sulfate (permanent) hardness as seen in the sample from Middle to Upper Silurian rocks in Northumberland County, Pa. Many of the waters from carbonate rocks would have to be softened before being used. However, for municipal supplies there is a rather wide tolerance and, insofar as domestic use is concerned, what is considered a troublesome hard water in one area may be considered as quite acceptable in another. For certain industrial uses, control of hardness may be highly critical.

Many waters from the Mississippian and Pennsylvania rocks of Pennsylvania and from the belt of Triassic rocks extending from Massachusetts to Virginia are also hard, with some of the hardness present as calcium sulfate. Although the rocks are largely sandstone, oxidation of minor accessory pyrite (iron sulfide) or solution of gypsiferous material probably accounts for the sulfate content of those waters.

Chloride in high concentrations is not commonly present in most waters except those from Silurian strata. However, it is generally true that water tapped in very deep wells is highly mineralized and in such waters chloride is one of the outstandingly, high constituents. Inasmuch as most samples represent waters that are being used for ordinary domestic or industrial purposes, few high chloride analyses are given in published reports. In Pennsylvania it has been found that water more or less ponded in deep synclines is commonly a high chloride water (see analysis from 496-foot well in Middle Silurian rocks, Blair County, Pa., table D-8). High chloride water from a 410-foot well in Devonian shale and sandstone in Tioga County, Pa., may have originated as seepage from deeper Silurian beds.

Ground waters from wells near the sea or tidal estuaries may be liable to gross contamination where wells are pumped heavily.

Iron is the troublesome constituent in many ground waters. The maximum concentration recommended by the U.S. Public Health Service is 0.3 mg/l. A concentration of more than 0.5 mg/l is ordinarily considered undesirable by most users. Many ground waters contain more than 0.5 mg/l of iron. Manganese is less commonly present but the recommended limit is only .05 mg/l. Some wells developed in Mississippian and Pennsylvanian sandstones and shales in Pennsylvania have an extremely high iron content, due largely to oxidation of accessory pyritic material. Shales in other areas are more likely to yield water higher in iron than other rock types. Water from the crystalline rocks commonly contain a little iron. In the southern Virginia Piedmont 10 samples out of 40 contained more iron than is considered acceptable. The maximum iron content in this group was 13 mg/l. In a group of 45 samples from wells in schist in the Washington area, 14 contained more than 0.3 mg/l or iron; of these, one had 34 mg/l of iron, and 10 less than 3.6 mg/l. This seems a fair enough characterization of the occurrence of iron in waters from the Piedmont crystalline rocks. In 27 samples from crystalline rocks in Maine, only 3 contained more than 0.3 mg/l of iron. In the Shetucket and Quinebaug River basins of Connecticut, the median iron concentration of water from wells ending in crystalline rocks is .07 mg/l although maxima of individual samples are 7.6 and 4.8 mg/l.

The hard carbonate waters commonly contain more than a little iron. However, out of 63 analyses of water from carbonate rocks from New York to Virginia, 20 contained more than the 0.3 mg/l. From the highly mineralized samples from Upper Silurian beds, another 8 samples in a group of 17 contained more than 0.3 mg/l of iron, a few much more.

Fluoride is ordinarily low in samples from wells ending in hard rocks.

Silica tends to be high in the crystalline rocks of the Piedmont, ranging commonly from 20 to 40 mg/l. In New England, however, silica in water from rock wells generally ranges from 10 to 20 mg/l. The weathered rock cover is presumably one factor in accounting for the greater silica and iron concentrations in the southern states. The presence of silica is critical where water is used for boiler feed. A few raw ground waters are suitable for low pressure boiler feed but considering other limiting factors, hardness and bicarbonate content particularly, most of them would require treatment before use.

Five of the 58 samples listed in which nitrate is determined are unacceptable for drinking water in that nitrate exceeds 45 mg/l, the upper limit set by the U.S. Public Health Service. Where lesser amounts of nitrate are derived from inorganic sources--commonly chemical fertilizer--water may be entirely free of organic pollutants and acceptable for drinking. However, if the lesser amounts of nitrate present are derived from organic sources, that is, human or animal wastes, the water may be carrying disease causing organisms. In such instances, the water may require a simple treatment before use by human beings.

Inasmuch as 11 out of 70 samples contain from 5 to 10 mg/l of nitrate and 17 out of 58 contain more than 10 but less than 45 mg/l of nitrate, it may be concluded that water from "rock wells" requires particular attention with respect to possible pollution.

In limestones and dolomites, contaminants may travel miles through open channels, but in other rocks water does not ordinarily move as freely and tends to be diluted with fresh meteoric waters by the time it moves very far. The carbonate rocks are initially more susceptible to pollution in that sinkholes and lesser solution openings from the surface may allow easy entrance of contaminants. Feed lots, turkey farms and sinkholes used for disposal of solid or liquid waste may commonly be point sources of organic contamination.

In most other rock types a thick cover of weathered rock allows surficial fluids to filter through rather slowly. Where there is slow passage from the surface to the water table, plant and biochemical action will tend to break down pollutants, as happens in the common practice of spreading animal manure and chemical fertilizers on farm fields.

One of the most highly contaminated ground-waters at hand shows a nitrate content of 159 mg/l and a chloride content of 94 mg/l. This is from a 78-foot well in carbonate rock in the Shenandoah Valley of Virginia. Somewhat lesser but still excessive nitrate is seen in analyses of water from wells in schist and gneiss listed in table 8.

In a report on ground water in the Washington, D.C. area, the phosphate content of well waters from metamorphic rocks (gneiss,

TABLE D-8.---CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS

(Constituents in milligrams per liter)

Geologic age	Precambrian									
Type of rock	Marble				Gabbro			Gneiss		
County State	Kings N.Y.	Chester Pa.	Chester Pa.	Loudoun Va.		Chester Pa.		Rockland N.Y.	Delaware Pa.	
Depth (feet)	600	98	69	83		165		205	67	
Silica (SiO_2)		12	22			32		22	34	
Iron (Fe)	.1	.03	.05			.05		.2	.08	
Calcium (Ca)		15	52	22		8.4		45	16	
Magnesium (Mg)		6.0	29			4.7		10	6.9	
Sodium (Na)		6.1	8.9			3.6		7.4	6.8	
Potassium (K)		8.1	1.4			1.2		1.9	1.9	
Bicarbonate (HCO_3)	322	51	256	32		34		175	23	
Sulfate (SO_4)		8.8	13	5		3.0		19	14	
Chloride (Cl)	32	11	17	28		2.6		3.6	6.2	
Fluoride (F)								.3		
Nitrate (NO_3)	7.4	17	15	51		16		.0	57	
Total Dissolved Solids	606	109	271			82		195	150	
Total Hardness as $CaCO_3$	390	62	249	116		40		154	68	
pH								7.4		

TABLE D-8.---CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)
(Constituents in milligrams per liter)

Geologic age	Precambrian									
Type of rock	Granite				Diorite		Schist			
County State	Henrico Va.	Chesterfld Va.	Putnam N.Y.		Putnam N.Y.		Fairfax Va.	Kings N.Y.	Chester Pa.	Lancaster Pa.
Depth (feet)	206	386	208		227		52	140	151	63
Silica (SiO_2)	26	17					20		87	11
Iron (Fe)	.10	.03			.05		.14	.1	.12	1.9
Calcium (Ca)	6.5	67					8.1		24	4.6
Magnesium (Mg)	.6	5					4		13	1.7
Sodium (Na)	6.7	197					6.9		39	
Potassium (K)		14					1.8		3.2	
Bicarbonate (HCO_3)	32	126	49		43		30	81	27	24
Sulfate (SO_4)	.6	468	13		20		2.2		15	4.2
Chloride (Cl)	4	24	2.4		29		7.0	20	79	4
Fluoride (F)		3.4								
Nitrate (NO_3)	.1	.10					12	1.6	67	6
Total Dissolved Solids	67	857	42		149		72	308	261	55
Total Hardness as $CaCO_3$	19	188	109		90		37	135	113	18
pH			7.		7					

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Precambrian									
Type of rock	Schist		Serpentine				Greenstone			Quartzite
County State	Washington Md.		Delaware Pa.	Chester Pa.	Chester Pa.		Loudoun Va.	Washington Md.		Lancaster Pa.
Depth (feet)	223		85	129	100		704	340		127
Silica (SiO_2)	.19		23	34	40		27	22		41
Iron (Fe)	.19		5.4	.42	.28		.22	.89		.53
Calcium (Ca)	35		7.2	6.6	2.1		26	6.6		2.
Magnesium (Mg)	8.7		5.6	25	76		5.4	1.2		1.4
Sodium (Na)	6		3.6	1.6	4.2		8.5			.6
Potassium (K)			1.0	.9	1.0		5.6			.6
Bicarbonate (HCO_3)	145		27	129	329		94	47		24
Sulfate (SO_4)	14		8.8	8.3	8.5		21	1		1.6
Chloride (Cl)	3		5.5	2.4	30		3.0	3.4		1.5
Fluoride (F)	.1									
Nitrate (NO_3)	.1		14	6.3	2.7		4.0	.2		
Total Dissolved Solids			111	131	333		143	72		27
Total Hardness as $CaCO_3$	123		41	119	317		87	21		19
pH	7.4							6.6		

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Precambrian	Lower Cambrian					Upper Cambrian			
Type of rock	Quartzite	Dolomite					Dolomite			
County State	Washington Md.		Clarke Va.	Augusta Va.	Chester N.Y.		Washington Md.	Frederick Va.	Fulton N.Y.	Cumberland Pa.
Depth (feet)	110		150	560	225		303	363	100	120
Silica (SiO_2)	14			9.2	12		12			13
Iron (Fe)	.10			.01	.19		.02		.15	.78
Calcium (Ca)	34		58	13	72		61	124		67
Magnesium (Mg)	3.3		30	7.3	.19		2.8	20		9.1
Sodium (Na)	1.7			.7	10		28	9.8		1.6
Potassium (K)				1.3	1.7					1.2
Bicarbonate (HCO_3)	291		294	74	237		230	302	146	204
Sulfate (SO_4)	27		11	2.0	41		9	26	18	7.7
Chloride (Cl)	75		4.0	.8	16		7.8	57	2.4	4.9
Fluoride (F)	.4						.2			
Nitrate (NO_3)	7.5		18	.7	26		18	72		29
Total Dissolved Solids	282		292	64	314		264	480	170	240
Total Hardness as $CaCO_3$	268		268	62	158		164	392	148	205
pH	7.8						7.6		8.1	

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Cambro-Ordovician			Lower Ordovician						
Type of rock	Limestone			Limestone						
County State	Columbia N.Y.	Berkshire Mass.		Frederick Va.	Page Va.	Rockingham Va.	Lancaster Pa.	Fulton N.Y.		
Depth (feet)	81	370		1432	223	40	18	141		
Silica (SiO_2)		6.6		96		6.6	12			
Iron (Fe)	.35			.26		.12	.06	.8		
Calcium (Ca)		23		98	75	144	66			
Magnesium (Mg)		13		30		20	14			
Sodium (Na)		1.1		14	4.6	40	4.6			
Potassium (K)		.7		4.8		5.9				
Bicarbonate (HCO_3)	300	133		394	284	328	228	268		
Sulfate (SO_4)	13	3.8		44	4	147	23	8.9		
Chloride (Cl)	2.0	1.4		9	5.0	63	43	175		
Fluoride (F)										
Nitrate (NO_3)		.6		13		26	19			
Total Dissolved Solids	275	120		409		643	260	547		
Total Hardness as $CaCO_3$	300	109		368	234	442	222	220		
pH	7.5	7.7								

TABLE D-8.---CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Lower Ordovician									
Type of rock	Dolomite				Shale					
County State	St. Lawrence N.Y.	St. Lawrence N.Y.	St. Lawrence N.Y.		Saratoga N.Y.	Augusta Va.	Montgomery N.Y.	Greene N.Y.		
Depth (feet)	285	316	216		322	179	185	342		
Silica (SiO_2)	12	10	6.4		12	68				
Iron (Fe)	.09	.14	10		.09	.02	.6	20		
Calcium (Ca)	80	35	2290		60	122				
Magnesium (Mg)	19	16	898		12	24				
Sodium (Na)	18	5.3	4190		75	21				
Potassium (K)	2.6	1.5	96			1.0				
Bicarbonate (HCO_3)	260	155	99		288	270	432	406		
Sulfate (SO_4)	79		527		90	58	33	76		
Chloride (Cl)	6.0	24	12800		21	70	7.8	4.8		
Fluoride (F)	.3	.3	1.1		.1					
Nitrate (NO_3)	.4	.3	12		2.1	84				
Total Dissolved Solids			20900		406	649	446	1050		
Total Hardness as $CaCO_3$	278	153	9240		199	403	220	100		
pH	8.0	7.4	7.0		7.9		7.9	9.3		

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)
(Constituents in milligrams per liter)

Geologic age	Lower Ordovician			Middle Ordovician				Lower Silurian		
Type of rock	Slate			Limy Shale				Sandstone		
County State	Dutchess N.Y.	Prince Wm. Va.		Northampton Pa.	Frederick Va.			Junius Pa.	Rockingham Va.	Monroe Pa.
Depth (feet)	300	127		400	95			1600	40	
Silica (SiO_2)	.17			28	19				9.2	
Iron (Fe)				.23	.04			.8	2.2	
Calcium (Ca)				27	144				38	14
Magnesium (Mg)				7.9	19				4.1	14
Sodium (Na)				3.6	16				2.3	
Potassium (K)				1.8	1.4				2.1	
Bicarbonate (HCO_3)	244	147		74	409			225	92	85
Sulfate (SO_4)	42	38		44	105			1380	29	12
Chloride (Cl)	10	5		1.8	16			5	3.5	30
Fluoride (F)										
Nitrate (NO_3)				.10	3.8				9.8	1.9
Total Dissolved Solids	346			150	539			2670	151	95
Total Hardness as $CaCO_3$	20	132		100	438			1520	112	90
pH	8.7									

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Middle Silurian				Upper Silurian					
Type of rock	Dolomitic Limestone				Shale and Limestone					
County State	Lycoming Pa.	Dauphin Pa.	Blair Pa.		Montour Pa.	Northumberland Pa.	 Pa.	Perry Pa.	Allegheny Md.	
Depth (feet)	302	140	496		200	240	190	308	202	
Silica (SiO_2)	.6				7.2					
Iron (Fe)	0.16	4.7			.09	1.2		.07	.05	
Calcium (Ca)	152	24	310		30	436	28	73	126	
Magnesium	40		69		13	87	6.1	32	32	
Sodium (Na)	129	29	453		1.9	93	11			
Potassium (K)	129				1.0	93	11			
Bicarbonate (HCO_3)	105	26	163		135	169	129	258	337	
Sulfate (SO_4)	470	140	141		10	1,266	9	85	215	
Chloride (Cl)	175	10	1250		2.1	136	2	4	14	
Fluoride (F)										
Nitrate (NO_3)	1.6	3.8			6.7	0.5	.4	9		
Total Dissolved Solids	1019	239	2303		152	2,102	124	335		
Total Hardness as $CaCO_3$	544	122	1058		128	1,447	95	314	444	
pH									7	

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Middle Devonian							Upper Devonian		
Type of rock	Shale		Limestone					Shales and Sandstone		
County State	Seneca N.Y.		Aroostook Me.	Aroostook Me.	Seneca N.Y.	Greene N.Y.		Sullivan N.Y.	Delaware N.Y.	Wyoming Pa
Depth (feet)	75				165	175		150	420	144
Silica (SiO_2)	8.2		9.5	6.1				5.4	7.9	16
Iron (Fe)	.16		.02	.02	.18	.35		.07	1.6	.04
Calcium (Ca)	94		66	45				19	20	46
Magnesium (Mg)	26		14	5.2				2.6	5	9.5
Sodium (Na)	20		30	2.5				2.4	87	23
Potassium (K)								1	13	1.7
Bicarbonate (HCO_3)	284		181	135	407	146		58	66	183
Sulfate (SO_4)	109		23	16	51	35		8.2	21	12
Chloride (Cl)	20		78	5.5	19	1.8		2.6	126	28
Fluoride (F)			.1	.2					.2	
Nitrate (NO_3)	12		4.3	4.9				6.7	2.8	.75
Total Dissolved Solids	477		404	154	470	185		80	308	223
Total Hardness as $CaCO_3$	341		222	134	190	92		58	71	154
pH	8.2		7.5	7.4	7.8	7.6		7.3	6.5	

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Lower Devonian						Middle Devonian		
Type of rock	Limestone				Sandstone		Shale		
County State	Montour Pa.	Huntingdon Pa.	Allegheny Md.		Allegheny Md.		Shenandoah Va.	Pike Pa.	Huntingdon Pa.
Depth (feet)	230	94	558		268		122	204	
Silica (SiO_2)			94						
Iron (Fe)			.11				34		6.1
Calcium (Ca)	88	114	143		15		10	10	45
Magnesium (Mg)		11	41		1.1				
Sodium (Na)	106	37	13		8.4		6.3	6	3
Potassium (K)			4.6						
Bicarbonate (HCO_3)	248	201	216		44		92	45	83
Sulfate (SO_4)	175	20	.335		4		12	4	60
Chloride (Cl)	39	150	.13		10		4	2	33
Fluoride (F)			.6		.2				
Nitrate (NO_3)		17	6.2		6.6		.2	.1	.10
Total Dissolved Solids	514	448	693					46	
Total Hardness as $CaCO_3$	210	330	518		42		80	32	171
pH					7.4				

TABLE D-8.--CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Upper Devonian		Mississippian			Pennsylvanian		
Type of rock	Shales and Sandstone		Shales and Sandstone			Sandstone		
County State	Lackawanna Pa.	Tioga Pa.	Elk Pa.	Potter Pa.	Cambria Pa.	Sullivan Pa.	Somerset Pa.	Allegheny Md.
Depth (feet)	500	410	120	130	363	65	130	200
Silica (SiO_2)	12					7.8		4.4
Iron (Fe)	.02	.48	2.8	1.7	26	.79	27	.02
Calcium (Ca)	37	82	54		72	24	40	6
Magnesium (Mg)	5	17	9.3		21	4.9		19
Sodium (Na)	15	1132	118		125	9.8	7	
Potassium (K)	2.2					3.2		
Bicarbonate (HCO_3)	168	197	193	30	138	53	3	211
Sulfate (SO_4)	4.5	7	67	6	313	41	117	83
Chloride (Cl)	2.2	1820	142	9	70	8	1	6
Fluoride (F)								
Nitrate (NO_3)	.15		1.7	4.7	.1	5.9	.10	
Total Dissolved Solids	162	3155	487	54	669	135	168	370
Total Hardness as $CaCO_3$	113	275	173	52	266	80	111	251
pH								6.9

TABLE D-8.---CHEMICAL ANALYSES OF GROUND WATERS FROM CONSOLIDATED ROCKS. (continued)

(Constituents in milligrams per liter)

Geologic age	Pennsylvanian			Triassic						
Type of rock	Sandstone			Sandstone						
County State	Somerset Pa.	Elk Pa.		Rockland N.Y.	Montgomery Pa.	Hartford Conn.	Hartford Conn.	Prince Wm. Va.	Montgomery Pa.	
Depth (feet)	75	235		413	916	63	602	505	100	
Silica (SiO_2)				11	28	10	14	38	22	
Iron (Fe)		9.2		.2	3.9	1.5	.08	1.1	.2	
Calcium (Ca)	144			14	180	95	27	31	55	
Magnesium (Mg)	36			14	32	26	10	23	20	
Sodium (Na)	4			9	27		2.3	12	14	
Potassium (K)				3.6	1		.8	1.4	2.2	
Bicarbonate (HCO_3)	130	39		129	180	75	80	219	202	
Sulfate (SO_4)	388	3		6.9	420	19	31	5.8	40	
Chloride (Cl)	4	.4		2.5	18	245	5.6	5	18	
Fluoride (F)				.1	.2		1		.2	
Nitrate (NO_3)	.9			3	2.8		18	1.8	19	
Total Dissolved Solids	641	37		118	805	722	155	202	307	
Total Hardness as $CaCO_3$	508	36		93	581	387	109	172	219	
pH				7.9	7.4					

schist, serpentine) is shown to range from zero up to 0.3 mg/l in most instances, but in one analysis, a phosphate content of 2.1 mg/l is shown. The same analysis shows an excessively high nitrate, 48 mg/l, and 18 mg/l of chloride, suggesting intensive local pollution.

Most ground waters in hard rock formations are alkaline.

CHAPTER V

GROUND WATER FROM GLACIAL DEPOSITS

OCCURRENCE

During the Ice Age, the northern part of the North Atlantic Region was entirely covered by a continental ice sheet many hundreds of feet thick. With the advance of the ice sheet, weathered rock material was scraped off the surface and incorporated in the ice and later redeposited as till. Valleys were deepened and in places interstream divides were punched through.

With amelioration of the climate, forward movement of the ice ceased, the ice began to melt and the ice front slowly receded northward. Huge blocks of ice lingered in many valleys and melted _in situ_. Heavily laden torrential streams from the melting ice, augmented by normal precipitation, brought about a bewildering complexity of erosional and depositional effects. With this gradual dissipation of the ice, drainage patterns underwent a series of twistings and turnings as melt waters sought newer and ever lower escape channels. Many older outlets were blocked by deposits of till or gravelly sand and new channels became permanently established. Early glacial stream deposits were left high and dry on the sides of a great many of the present valleys and still later deposits filled in at lower elevations. In a few instances major drainage channels were not regained by post glacial rivers. Those channels are now filled with glacial deposits and the courses of some preglacial rivers may now be marked by insignificant streams.

In a late glacial stage two other geologic events occurred, owing perhaps in large part to differential tiltings of the glaciated area. The one event, well exemplified in the Connecticut Valley, was the development of a lake stage, during which time earlier deposits at lower elevations were covered over by a thick layer of fine grained lake sediments. Here, and in many other smaller areas, the lake deposits are of importance in assessing the hydrologic framework. The other significant late glacial stage event, seen particularly along the New England Coast, was an invasion of the sea for some 10 or 20 miles inland. Marine clays laid down at that time now mask earlier permeable glacial deposits.

During the time of maximum advance of the ice, heavily laden melt waters tended to deposit most of their load at the ice front, thereby building up terminal moraines and, south of the moraines, outwash plain deposits. Long Island is an outstanding example of the land form resulting from these processes. The westward extension of that moraine across New Jersey and Pennsylvania is highly serrated and morainal till and outwash deposits occur in smaller units. Across the line of maximum ice advance streams flowing southward during the stages of waning ice carried coarse sediment varying distances southward beyond the limits of the ice itself and still later deposited stratified sand and gravel in stream channels in the formerly ice covered area.

GLACIAL AQUIFERS

With respect to ground-water potential, glacial deposits are of two extreme types. Till, a jumble of unsorted rock material, silt, sand, and boulders with some clay, commonly compact, is a very poor aquifer, whereas the coarser water sorted sediments, gravel and sand, are some of the best aquifers in the North Atlantic Region.

The complexity of depositional environment, barely touched upon in the preceding paragraphs, is such that overall generalizations of the disposition of glacial deposits is made with difficulty. However, the complex glacial stage history of many areas has been unravelled, a large number of well logs and well performance records are at hand, and an overall generalization may be made that within the glaciated area of the North Atlantic Region the highly permeable sands and gravels are present in valleys nearly everywhere at intermediate and low altitudes and, with few exceptions, offer the best opportunities for development of ground-water supplies. These are shown on plate D-1B.

In almost no instance can it be said that a river or large stream is underlain or bordered by coarse glacial sands continuously. Stratified glacial deposits may be present along almost the whole length of a stream but due to the cut and fill action during the depositional cycle, the valley will be floored and walled here and there by consolidated rock or by till. In places the glacial sands may be saturated in large part but elsewhere they may be only partly saturated or even dry. Deposits at lower elevations, representing a later filling of the space once occupied by ice, grade from coarse to fine and may interfinger with or be covered by later fine grained sediment, lake clays or marine clays, thus obscuring what may be aquifers of the highest quality.

In fewer areas, generally near the coast or in broad valleys, glacial streams wandered over low-lying gentle terrain and a more sheet-like deposition took place. Again, such deposits are quite variable in their makeup as well as in degree of saturation.

In a few places preglacial streams or river valleys were not reoccupied by post glacial streams. Choked with glacial deposits, generally water laid, such ancestral valleys are huge ground-water reservoirs with a high susceptibility to rapid recharge.

YIELDS OF WELLS IN GLACIAL DEPOSITS

Wells developed in thick glacial sands and gravels will yield up to 5 mgd. The yield is dependent on several factors: the thickness and extent of the aquifer, the grain size of the aquifer material, the source of recharge and the construction of the well itself. One well, at Schenectady, N.Y., is known to yield 5 mgd (million gallons per day) and a great many wells are recorded with yields ranging from 1 to 2 mgd. For the purpose of this study it is assumed that wells of 1 to 3 mgd magnitude can be constructed along the lower reaches of all the major rivers in the glaciated part of the North Atlantic Region although in some areas even higher yields may be possible. These wells cannot always be located in the immediate vicinity of the point of use. Owing to the variable and characteristically spotty nature of the glacial deposits, it may be necessary to site wells some distance upstream or downstream from the municipality or industry for which the water is intended.

From place to place large yield wells can be constructed at locations somewhat distant from major streams. Most of these locations lie along the course of abandoned stream channels, either preglacial channels or temporary intraglacial channels.

RECHARGE OF GLACIAL AQUIFERS

The question of source of recharge of the glacial aquifers is highly critical where large quantities of water are to be developed. Detailed studies in Connecticut and elsewhere have shown the amount of recharge averages about 1 mgd per square mile on sandy ground of low relief. Inasmuch as very large losses by evapotranspiration from the water table are indicated in water budget studies, with appreciable lowering of the water table much of this might be salvaged. Perhaps a recharge figure of about $1\frac{1}{2}$ mgd might be considered more realistic where maximum developments are contemplated in some glacial terrains.

However, most glacial deposits occur in patches or irregular bands. Many of these patches, although very well suited to development of high yield wells, will not receive enough local recharge to sustain discharges of 5, 10, or 15 mgd. Where the larger volumes are concerned, a nearby source of rapid recharge, ordinarily a large stream or river, is critical.

Where the glacial aquifer is relatively narrow, but of longer dimensions, as in some abandoned gravel-filled channels, ground-water underflow from upgradient may be sufficient to bring in appreciably large increments of recharge water to a well field. Underground recharge from adjacent consolidated rock bodies is thought to be small, but some (much?) direct runoff from surrounding hills may infiltrate the low-lying valley aquifers.

The other critical factor to be considered in development of glacial aquifers is storage. It must be assumed that there are periods of low recharge or no recharge and in some locations wells will draw to a large extent or even entirely upon storage water. A square mile of sandy reservoir in which water level was lowered 50 feet might yield 2,090 million gallons of water (27,878,400 sq.ft. x 50 ft. x 7.48 gal. x 20%). That volume is equivalent to a discharge of about $11\frac{1}{2}$ mgd for a period of 6 months. It follows, then, that in some fairly large areas with poor hydraulic connection to major waterways, tremendous quantities of water lie in dead storage. Although subject to limited recharge, large quantities of water, from 5 to 25 mgd, perhaps, might be pumped at moderate cost during times of drought to supplement existing supplies or to augment the flow of small rivers.

Having considered the potential of isolated patches of glacial terrain where sustained discharge of large quantities of water are unlikely, attention may be given to glacial sediments adjacent to small and large rivers. Assuming that highly permeable gravels are present, as they generally are, the amount of water that can be developed from wells is largely dependent upon the amount of water that can be induced to infiltrate from the river. Thus, adjacent to large rivers, on the generally narrow discontinuous bordering terraces made up of coarse glacial sediment, high yield wells might be spaced rather closely without great mutual interference. Detailed studies have been made in a few places that show exactly how much infiltration may be expected per unit reach of river for each foot of lowering of the water table beneath the river level. However, the many factors inherent in developing a well field are so widely variable that specific information of this nature is useful only as a generalization. What is more to the point for the purpose of overall evaluations is the knowledge that throughout the glaciated areas high yield wells have been constructed along most of the large rivers. As noted above, a great many of these wells yield less than 2 mgd; however, inspection of records shows that most of them do not develop all the sands present, some lack optimum well screens, most of them utilize only part of the total available drawdown and some are intended to produce only a few hundred gallons per minute. Hence, for planning purposes the potential yield is assumed to be 2 mgd per mile of reach from wells yielding about 1 mgd to perhaps more than 3 mgd. This assumption seems reasonable and perhaps even conservative. A very rough approximation of the volume of water that may be developed from glacial deposits is given in table 10.

A well development dependent upon infiltration of river water will be limited by the volume of river water available and further, as noted above, thick saturated glacial deposits will ordinarily be found only on somewhat lower ground, that is, perhaps in the lower two-thirds of a river's length.

TEST WELLS

The "bewildering complexity" of glacial processes referred to previously is sufficient to justify a statement that test wells are always necessary before constructing production wells in glacial sediments and that the locations should always be selected by a ground-water geologist who has the ability to mentally reconstruct the glacial history of the area. The test wells should be drilled by the cable tool method in order to insure penetration of all the material down to bedrock.

Jet drills and "wash" drills are particularly unsatisfactory for test purposes. In the part of this report addressed to costs of drilling, it is shown that possible savings in utilizing this method of testing are woefully small when compared to the risk of failing to reach a high-yield aquifer.

Considering the variability of glacial sediments and the low cost of test holes when related to cost per thousand gallons of water production from a high-yield well, as brought out in part 2 of this paper, it will be desirable in some areas to drill more than one or two test holes before constructing a production well.

ADVANTAGES AND DISADVANTAGES OF WELLS IN GLACIAL AQUIFERS

From an overall point of view, it is important to appreciate the relationship of "glacial ground water" to surface water resources.

Obviously, in wells dependent upon infiltration of river water for recharge no additional water is gained in the system. Ground water discharge is simply an additional load upon the river flow (fig. D-3). If the river flow is critical at any of its stages, such wells may not provide a more satisfactory means of supplying water for a municipality or industry than pumping directly from the river, except for quality considerations. Less commonly discharge from wells in glacial deposits will depend on ground storage to a greater or lesser during time of low flow (fig. D-4B), in which additional water becomes available to the system at that time.

A great advantage is seen where river flow is not critical and where the river water contains filterable pollutants. In such instances water withdrawn from the river by wells would be cleaned of much or perhaps all of its contaminants, particularly pollution resulting from raw or incompletely treated sewage. The cost of wells would be more than offset by capital costs and maintenance of a filter plant and such intake structures and pipeline as might otherwise be necessary to draw directly upon river water.

The economic advantage of locating a dependable water supply near the point of use as opposed to the cost of a long pipeline to a somewhat distant surface reservoir is obvious. This is particularly applicable where only a few million gallons of water a day are needed.

A disadvantage in some areas is the occurrence of iron or manganese in water from glacial deposits. Some ground waters from glacial deposits are initially high in iron and instances are known where municipal water supplies, initially iron-free, have increased in iron content after a period of many months. Why water from some glacial beds is high in iron or becomes so is not known. It is known, however, that in any one area one possible source of ground water may be iron-free and a nearby source quite high in iron. Hence, it is likely that more than a minimum of test drilling will be necessary in some areas to secure a supply that is at least initially iron free.

On the other hand, iron removal treatment is not particularly expensive or difficult to accomplish. Where an otherwise economical supply of ground water requiring treatment is available, the overall cost, including treatment, may still be less than the cost of a supply from some other source.

QUALITY OF WATER IN GLACIAL DEPOSITS

Water in glacial deposits is generally of good quality. Total dissolved solids is low, commonly 200 mg/l or less and hardness is low or, in fewer instances, only moderately hard.

The presence of iron in water from some glacial deposits has been touched upon. In no sense may it be said that those waters generally contain more than 0.3 mg/l of iron or more than .05 mg/l of manganese. According to analyses given in published reports in the Connecticut basin in Connecticut, 7 samples out of 62 listed were high in iron or manganese. In the Millers River basin of Massachusetts 22 samples out of 72 contained "unacceptable" iron or manganese although only 6 of the 22 contained more than 1 mg/l of iron. In southeastern Massachusetts only 1 sample out of 15 was high in iron. In southeastern New Hampshire 3 out of 34 samples were found high in iron or manganese. In Maine 21 out of 25 samples were low in iron and manganese and 3 had much more than .03 mg/l of manganese and .05 mg/l of iron (see table D-9).

In New England glacial sediments contain few carbonate rock constituents and hence range from very soft to only moderately hard.

In New York (excluding Long Island), Pennsylvania, and New Jersey glacial aquifers are made up in varying degrees of limestone and dolomite fragments and water in such beds is more commonly hard. Further, in those areas glacial sediments may receive seepage from Paleozoic carbonate rocks that contain highly mineralized waters. One of the samples from Tioga County, Pennsylvania (table D-9) is not only hard but contains 465 mg/l of chloride. The sample shown from Schoharie County, New York is very high in sulfate, probably due to solution of gypsum in locally derived glacial sediment or in underlying bedrock. In the vicinity of Upper Silurian outcroppings in New York State, glacial aquifers may be locally contaminated by high chloride waters.

Generally, glacial aquifers are highly permeable, circulation through them is relatively rapid, and the water is of good quality. However, in many instances water from glacial deposits is slightly acidic.

CHAPTER VI

ARTIFICIAL RECHARGE OF GROUND WATER

DESIRABILITY OF ARTIFICIAL RECHARGE

It has been brought out elsewhere that ground water accounts for the larger part of streamflow and that development of ground-water supplies, highly desirable as it is in many places, may not add greatly to the total available supply of water. Additional water can be made available to the precipitation-ground-stream system, however, by recovering losses due to evapotranspiration, by recycling of water, and by salvage of high flow components that ordinarily are wasted to the sea. It is on this last factor that this discussion is based.

TABLE D-9.--CHEMICAL ANALYSES OF GROUND WATERS FROM GLACIAL AQUIFERS.

(Constituents in milligrams per liter)

County State	York Me.	Kennebec Me.	Androscoggin Me.	Rockingham N.H.	Hartford Conn.	Hartford Conn.	Plymouth Mass.	Schenectady N.Y.	Nassau N.Y.	Nassau N.Y.
Depth (feet)	20	89	76		160	40	25	62	25	103
Silica (SiO_2)	5.6	13	18	8.7	12	12	4.8	6.5	5.4	27
Iron (Fe)	.11	.02	13	.04	.09	.42	.19	.05	3.3	2.8
Manganese (Mn)		.02	.24		.04	.97				.15
Calcium (Ca)	1.4	45	19	22	22	28	3.8	49	4	12
Magnesium (Mg)	.2	1.6	2.4	3.8	2.6	6.8	.8	8.6	1	2.5
Sodium (Na)	1.7	5.6	4.6	11	65	5.9	3.1	7.4	3	63
Potassium (K)	.3	3.6	2	5.2		.8	1.2	1.8	1.2	2
Bicarbonate (HCO_3)	7	138	69	48	180	41	4.	158	11	64
Sulfate (SO_4)	3.4	12	12	2.6	53	43	10	30	6.9	.2
Chloride (Cl)	1.1	6.2	1.2	17	2.8	5.9	5	7.2	3.9	6
Fluoride (F)	.0	.0	.2	.0	.2	.0	.1	.1	.0	.1
Nitrate (NO_3)	.0	.7	.1	11	.1	33	1.2	.3	1.9	.3
Total Dissolved Solids	18	160	103	139	249	167	35	187	35	100
Total Hardness as $CaCO_3$	5	119	58	71	66	98	11	155	14	41
pH	5.8	8.4	7.4	6.7	7.9	7	5.3	7.7	6.1	6.8

TABLE D-9.--CHEMICAL ANALYSES OF GROUND WATERS FROM GLACIAL AQUIFERS--continued

(Constituents in milligrams per liter)

County State	Suffolk N.Y.	Tioga Penn.	Tioga Penn.	Schoharie N.Y.
Depth (feet)	123	102	60	92
Silica (SiO_2)	19		15	
Iron (Fe)	2.8	6.1	.07	.6
Manganese (Mn)	.13			.4
Calcium (Ca)	22	75	64	
Magnesium (Mg)	14	20	12	
Sodium (Na)	168	278	8.9	
Potassium (K)			1.6	
Bicarbonate (HCO_3)	29	263	205	106
Sulfate (SO_4)	29	2	46	373
Chloride (Cl)	302	465	6.5	43
Fluoride (F)	.3			
Nitrate (NO_3)	.1	.5	.36	
Total Dissolved Solids	596	972	258	796
Total Hardness as $CaCO_3$	113	270	209	285
pH	6.1			7.7

Salvage of much high flow has been almost entirely accomplished by the building of dams. However, in more recent years thought has been given to using the great underground reservoir capacity for the same purpose. In California the storage of water underground, in some instances water pumped from streams in distant basins, is widely practiced and has proved to be economically feasible. In the midwestern states artificial recharge is being carried out from place to place. The technique is utilized to a more limited extent in the northeastern states.

Methods range from collecting storm runoff in pits to the building of elaborate canals and pipeline systems bringing in water to recharge basins or injection wells. Difficulties attend these efforts in places, depending on type of water used, the geological framework, the inhibiting effect of frozen ground, the injection device and perhaps other factors. Obviously, it will be well to collect pertinent data before recharge is attempted, even on a small experimental scale. Nevertheless, the concept is hydrologically sound and we may logically expect that our technological society will provide satisfactory answers to the problems that now exist in some areas. The attitude is taken, therefore, that mechanical problems can be solved eventually and attention will be given here to consideration of areas and situations where artificial recharge may be desirable.

PREREQUISITE CONDITIONS

In the arid West ground-water levels generally lie fairly deep below the surface and well below the level of ephemeral streams. Further, as in parts of California, ground-water levels have been greatly depressed by decades of heavy pumping. Hence, there is no difficulty in finding storage space for whatever recharge water can be made available. In the humid East, however, unsaturated storage space is not as readily located. Ground-water levels are fairly close to the surface in flat-lying and gently rolling ground and the ground-water reservoir is constantly "losing" water to streams and springs. Addition of water to the ground will be limited by space requirements and, further, increasing the slope of the water table will promote more rapid lateral migration of that water to the streams. To complete the analogy, it is difficult to fill a cup with water if the cup is already full.

The first problem then may be the manner of providing storage space in the ground. Heavy pumping during the summer season, a time of maximum demand and low streamflow, can be accomplished in certain areas without significantly affecting streamflow. Ground water levels will decline and space will then be provided for receiving and retaining excess water that becomes available in the colder months, either local surface runoff water salvaged by structures built for the purpose or water brought in from outside the area to be recharged. It should be noted at this point that drawing water levels down may promote additional natural recharge and as discussed above, may reduce evapotranspiration loss.

To the extent that recharge water is water otherwise wasted as part of the high flow stream component, an addition to the total available supply is gained.

Artificial recharge might be carried on throughout the year. In one midwestern locality, water is led by ditch or pipeline from an upstream point to a well field where it infiltrates the ground. Here the ground is replenished more easily and quickly than occurs by natural infiltration from a nearby river. The water withdrawn is, in this instance, filtered by its passage through the sandy aquifer. Here, it can be argued that recharge water used during the late summer months may be subtracting water from a critical low flow in the river (fig.D-3). The most desirable operation then will be one where enough water can be stored during the winter season to last through the summer season. This will require that the ground reservoir be large enough to satisfy the summer demand from storage plus moderate natural recharge (fig. D-4).

Of all the rocks in the North Atlantic Region sandy sediments have the greatest capacity for storing water. Although porosity may be as high as 40 percent of their volume, the amount of water that will drain from a sandy column upon lowering of the water table (specific capacity) ranges from 15 to 25 percent in medium to coarse grained sediments. A figure of 20 percent of the total rock volume still represents a large reservoir capacity. Each cubic foot of sand has a storage capacity of 1.5 gallons (7.48 gal. x 20%). A square mile of sandy reservoir in which the water level could be lowered 50 feet would have a capacity of 2,090 million gallons (27,878,400 sq. ft. x 50 x 7.48 gal. x 20%). This volume is sufficient to supply a city of over 110,000 with water, 17 mgd, for 4 months without recharge. However, inasmuch as recharge on sandy ground is about 1 mgd per square mile per day, a ground-water reservoir of the dimensions given would ordinarily be considered to be able to sustain a yield of 1 mgd (or less), as present practice goes.

Thus, with a 1 square mile ground reservoir with an average recharge of 1 mgd, we might pump 5 mgd, leaving an annual recharge deficit of 1,460 million gallons. Storage being 2,090 million gallons, it should be safe to pump 4 mgd in excess of average daily natural recharge providing that additional artificial recharge water can be provided during a high rainfall season to make up the imbalance. In this particular example the necessity for recharging an extra 1,460 million gallons in a 6-month winter period (about 8 mgd) might be difficult to achieve but is not outside the range of possibilities.

Muckel and Schiff (16) state that under favorable conditions, the infiltration rate in one test pond in the West was 11.6 feet per day but declined to 5.4 feet per day after 200 days. This figure translates into a recharge rate of 3,780,000 gallons a day per acre, decreasing to 1,760,000 gallons a day after 200 days. Taking an average rate of 2,500,000 gallons per day per acre (a little less than the arithmetical average) one acre might "yield" a recharge of 75 million gallons a month. Four acres of spreading basins might provide the 1,460 million gallons deficit referred to above in about 50 days operation. (Lateral movement of recharge water is probably necessary to maintain a high rate of recharge, hence spreading operations will undoubtedly function more efficiently where several smaller discrete basins are utilized rather than one larger basin.)

In the Santa Clara, Calif., Conservation District, 15 percolation ponds (pits in gravelly ground) ranging in size from 5 to 79 acres, accept recharge water at a rate ranging from about 1 to 3.8 feet per day per acre. The average is 1.4 acre feet per day or about 470,000 gallons per day per acre. According to the June 30, 1960, Annual Report of the organization, "When all facilities (both developed ponds and natural channels) are in full use, the District can percolate 860 acre-feet per day...over 280 million gallons per day! This amount of water would supply a city of 2 million people!"

These examples illustrate well enough the methodology that could be employed where conditions are favorable in greatly increasing the yield of a well field by utilizing water that might otherwise be wasted.

The degree of receptivity of spreading grounds, as opposed to pits or injection wells, depends upon the soil type (sandy or clayey, and content of organic matter), the type of cover material and of course, the permeability of the formation beneath the soil cover. Turbidity must be dealt with in all recharge operations. Bare soil tends to become compact, but soil covered with grass is highly receptive (18). The high infiltration rates referred to above were noted in test ponds covered with Bermuda grass (16). Intermittent flooding and drying is much more efficient than continuous flooding. Chemical treatment of the soil, e.g., use of gypsum on sodic clayey soils or where the recharge fluid is sodic, is beneficial in some areas. The techniques of water spreading by flooding, as touched upon above, or by ditches, furrows and pits, are outlined generally in the article referred to by Muckel and Schiff (16) and in an earlier paper by Mitchelson and Muckel (19). Obviously, plans for use of flood waters for spreading or other recharge operations should be as thoughtfully prepared as for any other water development operation.

In employing injection wells for recharge in sandy sediments, turbidity of the injection water must be lowered to a near minimum, dissolved gases may liberate bubbles that "clog" the pore spaces in the formation and chemical or biochemical actions may occur that form slimes.

However, on Long Island, due to regulations requiring the return of cooling water to the ground after use, recharge wells have been developed that are capable of returning as much as 1,000 gpm to the ground (20). Many of them were reported to have been in operation over 5 years without failing. At present, some 2,000 recharge pits on Long Island return an average of 80 mgd of storm runoff water to the ground.

In New Jersey, artificial recharge by bringing stream waters into lakes or trenches near well fields has been practiced for many years (21), at Perth Amboy, Old Bridge (Duhernal), Lake Mohawk, East Orange, and Princeton. In 1948, spreading operations were being carried out in eighteen localities in Massachusetts (22).

Before attempting large scale artificial recharge a great deal of exploratory drilling and test pumping may be required to gage the capacity of the formations to yield water to wells. The suitability of the ground with respect to acceptance of water through artificial recharge devices must also be assessed. The appreciable cost of gaining such information should not preclude consideration of the technique. Rather such costs should be viewed as normal preliminary costs, as in all engineering ventures.

A skilled ground-water hydrologist can, more times than not, make a preliminary appraisal that will be of the correct order of magnitude and show that further investigation is or is not economically feasible. Earth formations nearly everywhere assume characteristic patterns that are easily recognized by the initiated. Qualitative and, in a gross sense, quantitative assessment of aquifer response can frequently be estimated that will show that a development of certain magnitude lies within the realm of economic and hydrologic practicability or does not.

ARTIFICIAL RECHARGE OF THE VARIOUS AQUIFERS

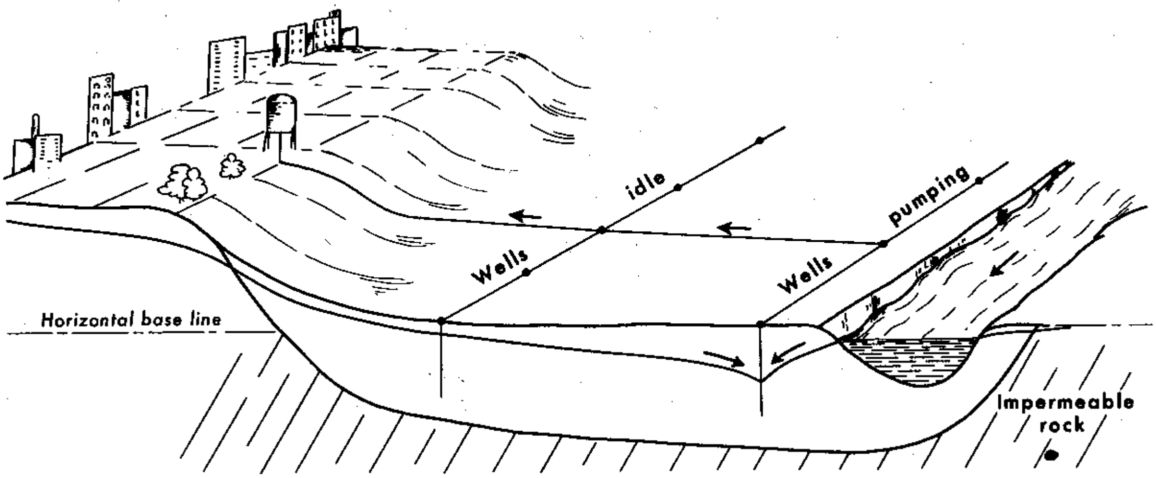
Glacial Deposits. The sandy sediments, the formations providing maximum storage space for artificial recharge water are, largely, the glacial and coastal plain deposits.

The sandy glacial deposits are those which have their greatest areal development in and adjacent to present streams and rivers with which they are hydraulically connected. On this account many of these deposits will not lend themselves to greater development by artificial recharge. Water added to narrow strips of sandy sediments immediately adjacent to water courses will tend to discharge the injection water rather quickly, in a matter of weeks or very few months.

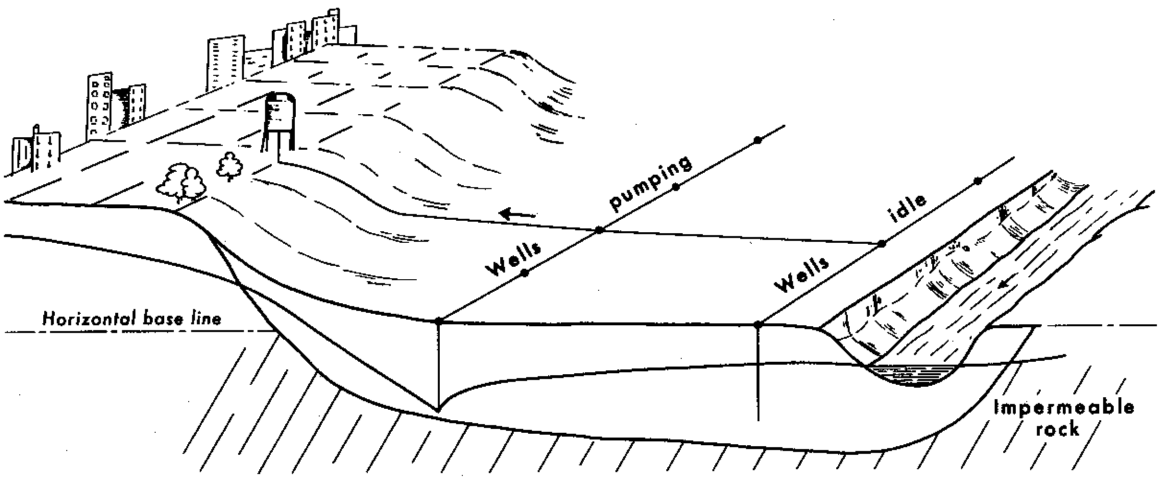
However, there are many areas where the bordering deposits are a fraction of a mile or even greater than a mile in width. Given the relatively slow rate of percolation of ground water under low hydraulic gradient, it can be assumed that a linear ground-water mound built up half a mile back from a river would tend to flatten very slowly under natural conditions, hence extra water would be retained that could be drawn upon in a low rainfall season. Depending on the dimensions of the area recharged, slow drainage of ground-water mounds would tend to increase the low flow of adjacent streams. Such ground-water mounds could be built up by diverting small streams to appropriate areas, by canalizing flow from the main stem from higher elevation upstream, perhaps in part as contribution to flood control, or by pumping water directly from the main stem back to recharge fields (fig. D-10). Artificial recharge in these sediments would most likely be most economically accomplished through pits, ditches, and spreading grounds.

From place to place thick fairly broad glacial deposits are present which have only tenuous connections with the major stream system of a basin. These may be ideal for artificial recharge development provided the sediments are reasonably permeable and that "extra" water is available during the high rainfall season.

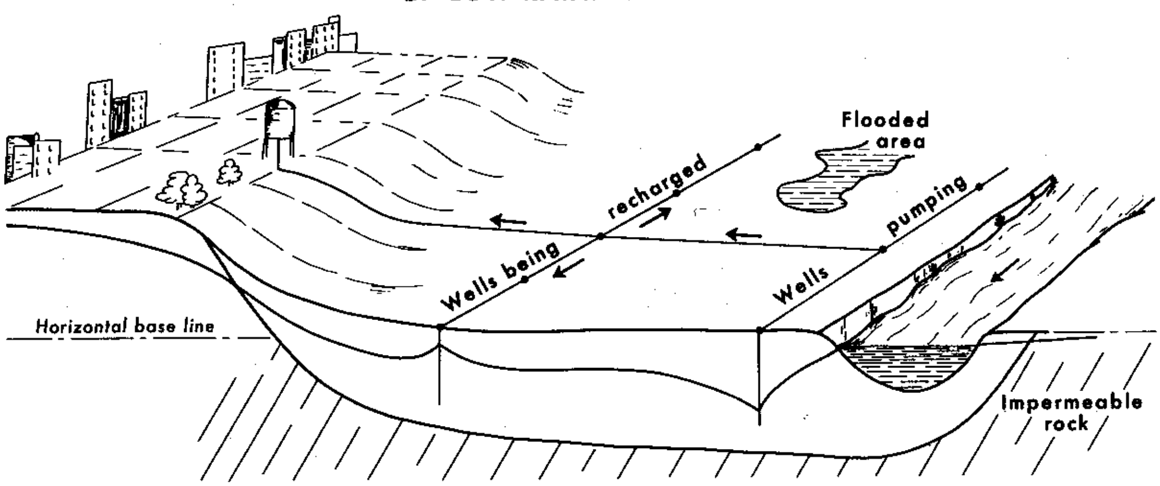
Such deposits might be drawn upon heavily in dry seasons without affecting critical low flows of major streams and recharged by one means or other in later higher rainfall periods. In addition to the artificial recharge devices ordinarily considered, the desirability of slowing down natural runoff by constructing distributaries in minor streams and low, even purposely leaky, dams should be considered.



A. NORMAL RAINFALL PERIOD



B. LOW RAINFALL PERIOD



C. RECOVERY PERIOD

Figure D-10.--Sketches showing method of salvaging part of high streamflow and increasing aquifer capability. Wells discharge stream water in large part in season of high streamflow (A). Streamflow in the low flow period (B) is only slightly affected by pumping because much of the ground water pumped is from storage. The deficiency in storage is made up in the succeeding higher rainfall and higher streamflow period (C).

Preglacial stream channels, now filled with a high proportion of permeable sediments and which are presently drained by very small streams may be particularly susceptible to development by means sketched out above without affecting critical low flows of major streams. Many such abandoned channels are known and still others will, no doubt, be located from time to time.

In many places thick glacial aquifers of high permeability are overlain by silty and clayey deposits. Here recharge by pits and canals may not be effective and artificial recharge through injection wells will be necessary. However, as in some other aspects of artificial recharge, not much is known of rates of recharge that might be expected from inexpensive recharge pits in finer grained sediments. Considering the highly variable nature of glacial deposits, satisfactory results might be obtained in some areas or in particular sites that at first seem unsuitable for effective recharge. Additionally, a broad silty or clayey cover overlying permeable deposits may be coarser textured, even sandy, where such deposits lap up against a hard rock highland. Such locations may be ideal from the point of view of maximum water retention if artificial recharge there can be carried out successfully.

Coastal plain water table formations. Artificial recharge in areas where artesian formations crop out along the Fall Zone would be carried out in much the same manner as depicted for the glacial sediments. As noted elsewhere in the text, in large part these sediments are saturated and potential infiltration water is rejected. Here, too, maximum development of ground water can only be achieved by using that resource. However, where maximum pumping of (water table) water in the outcrop zone takes place, the volume of water flowing downdip to artesian wells may be diminished and in such instance artificial recharge would be desirable.

Where a highly polluted major stream crosses or runs parallel to the outcrop belt, heavy ground-water discharge along the outcrop and even from downdip artesian wells will tend to draw in that polluted water. Artificial recharge in the area between the polluted river and the threatened well field would be helpful in arresting movement of pollutants into the formation. It follows, of course, that if industrial and other development is great in the area, there may be difficulty in acquiring a significant quantity of "extra" water locally for recharge and even construction of a series of many small dams to retain storm runoff water for additional recharge may be impractical.

The vast reservoir capacity of the Pliocene-Pleistocene formations on Long Island, and in the coastal plain of New Jersey and for some small distance southward offers great opportunities for the utilizing of artificial recharge. The Long Island reservoir is already heavily drawn upon and, speaking broadly, is approaching the limits of its development. However, as a ready-made reservoir it offers the same opportunities for development that are seen and utilized in California. Here, too, the recharge water is the problem. It may be assumed that the supply brought into New York City from upstate New York or elsewhere is highly variable and that at times the demand will be less than the supply whether the supply be real or potential. At such times of available extra water, underground storage on Long Island may be utilized and in other seasons, the water pumped back to New York City or be permitted to remain as an addition to the Long Island supply. The costs of underground storage on Long Island may not appear great if those costs are balanced against the necessity of providing excess pipeline capacity into New York City where surface water storage sites are essentially unavailable.

The Cohansey surficial formation of eastern New Jersey is susceptible to artificial recharge at low cost. The formation is greatly under-utilized at present and the first step towards its development would be to draw down the water table by using ground water, upon which greater acceptance of precipitation would be fostered and evapotranspiration losses would be reduced. With still further draft, storage space would be provided for additional recharge water. However, the possibility of providing water for artificial recharge to eastern New Jersey from outside sources, such as the Delaware River, seems remote.

Lack of water from outside sources would restrict the utilization of grand scale artificial recharge also on the Delmarva Peninsula where Pliocene-Pleistocene deposits are fairly thick. The most that might be done there would probably be the adoption of highly effective measures now taken on Long Island to salvage storm runoff by infiltration pits.

Coastal plain artesian formations. The artesian formations, particularly the basal Cretaceous aquifer, are a potential source of large supplies of ground water and are heavily drawn upon in many places today. Although large, the supply is not unlimited and in areas of intensive development artesian water levels tend to be greatly depressed and an eventual limitation on total additional ground-water development can be foreseen. In many areas, this action can be forestalled to a greater or lesser degree by recharging with water from the shallow surficial formations, water now under-utilized or going almost entirely to waste. Water in rather thin terrace deposits of Virginia and to some extent in Maryland and Delaware would be expensive to salvage by conventional means. Recharge wells so constructed that water would flow by gravity from near the base of a partly saturated terrace to deep artesian formations in which the artesian head is depressed might do much to restore pressure head and add appreciable water to the system (fig. 11). In addition to a connector well device, similar to that shown in figures D-11 and 12, consideration may be given to large diameter "wells" without casing and filled with permeable sand or gravel that permit water to pass from one formation to the other. These may be practical where the intervening impermeable bed is not more than a few tens of feet thick. Development of such structures to prevent clogging may be difficult.

In the Coastal Plain of western Maryland and Virginia the surficial terrace formations are generally 30 feet or less in thickness. No individual terrace is continuous for any great distance although many are more than a mile in length and more than half a mile wide. Hence, because of their lack of continuity and limited thickness, storage capacity is small and with few exceptions, utilization of the aquifer is impractical except for supplying small domestic needs.

Recharge to these shallow sandy beds, about 1 mgd per square mile, is roughly 3/4 billion gallons a day in western Maryland and Virginia. Nearly all of this water flows into estuarine streams and the bay.

Salvage of an appreciable fraction of this water through artificial recharge of deep artesian aquifers may afford an answer to critical problems in the future. Several possible methods of capturing the natural recharge of these surficial beds, and otherwise utilizing them, are illustrated in figure D-12.

Shallow pumped wells hooked in tandem could function as a source of water to recharge a deep well. The methodology is simple but costs might be high. Individual connector wells (fig. D-11) would also be somewhat expensive. If available water were supplemented by water pumped from the river and spread on the land (fig. D-12) during times of higher flows, if secondary treated sewage effluent were sprayed upon the land (as discussed below in this chapter) or if (untreated?) storm water runoff from a nearby urban area might be used as supplemental water, utilization of shallow wells or connector wells might prove to be economically feasible. Drain tiles bringing natural and artificial recharge water to a deep recharge well might be less expensive in that pumping and maintenance of the system would be negligible and most of the land area affected might also serve for some other uses.

Tertiary treated sewage may also be an acceptable source of recharge water for artesian aquifers. From an aesthetic point of view, it may be noted that the tertiary treated effluent is again filtered as it moves from the recharge well to the supply well (at left, fig. 12).

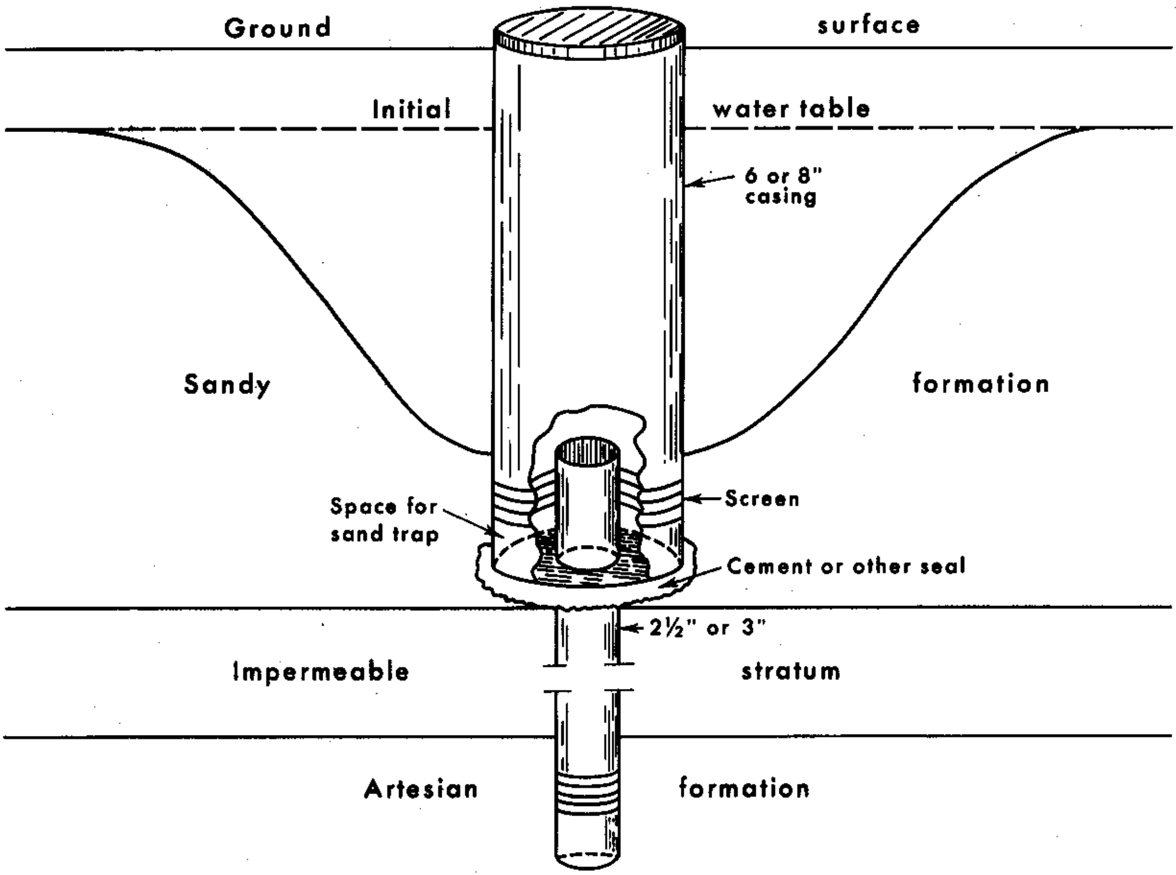


Figure D-11.--Sketch of a suggested design for a connector well intended to capture ground water from relatively thin surficial sandy Coastal Plain beds. Where artesian head is low relative to the surficial formation, whether due to the high topographic position of those beds or to depressed artesian head resulting from heavy withdrawals, water otherwise running off to estuaries will flow to the artesian reservoir by gravity.

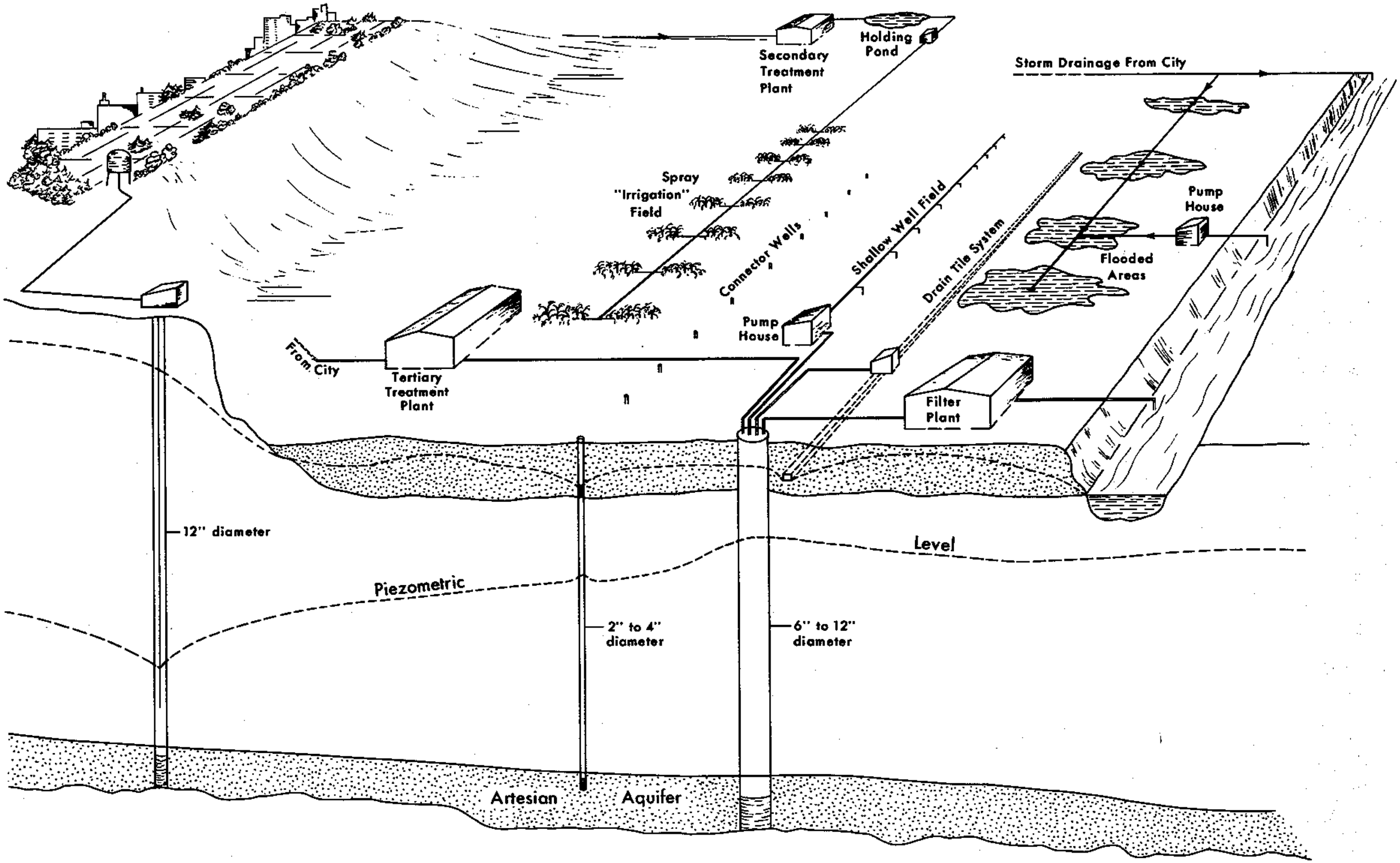


Figure D-12.--Diagram showing artificial recharge of an artesian aquifer by surficial ground water. The near-surface aquifer is in turn recharged by flood water, storm drainage, and treated effluent.

Where artesian water levels are strongly depressed (fig. D-7) and the volume of water to be recharged is not great, recharge by gravity flow may work effectively. Where artesian levels are somewhat high relative to land surface, and the volume of water to be recharged is greater, water may need to be recharged under pressure.

The under-utilized Cohansey formation with its great storage potential and high recharge rate might achieve its maximum usefulness as a source of recharge water for the artesian formations of New Jersey. Assuming a maximum development of artesian supplies a few miles southeast of Delaware River, recharge wells still farther to the southeast would help maintain high artesian pressures that would be beneficial to water users from a cost point of view and would tend to lessen the tendency to draw in polluted Delaware River water. A second line of recharge wells still farther downdip would create a pressure barrier between the artesian wells and the formational salt water front. It is probably safe to say that eventually such a pressure barrier will have to be created if maximum utilization of existing supplies is ever to be attempted. Similar barriers will need to be effected by injection wells in other parts of the Coastal Plain and in all foreseeable instances the water will be derived from shallow ground-water aquifers.

Artificial recharge offers some enormous advantages in those parts of the Coastal Plain where artesian strata are now saturated with salt water. Here fresh water, available in largest part from shallow ground-water reservoirs, may be stored in the brackish water artesian beds through injection wells. Storage under such conditions has been demonstrated (23, 24) and further work to determine quantitative and other factors involved is underway in a few places.

Some shoreline areas along the Atlantic Coast may eventually find this method of increasing their supply advantageous. With a short fairly high summer demand and a long high rainfall winter season, the rather large volume of recharge water available from shallow wells or from generally small capacity surface reservoirs may suffice. Elsewhere pipelines from fresh-water artesian wells updip in all of the Coastal Plain or from "inland" high yield water-table wells in New Jersey, Delaware and eastern Maryland will bring water in for recharging saline water artesian formations.

Carbonate rocks. In many areas carbonate rocks have a very high permeability and although their storage capacity (porosity) may be much less than that of sand and gravel formations it is still great. Some limestones and dolomites in the North Atlantic Region are quite massive and their hydrologic characteristics are scarcely better than those of the crystalline rocks. Others have a high permeability, as seen in the yields of some wells in the Cambro-Ordovician formations, and a storage capacity of about 4 percent (10).

However, the storage capacity of the best North Atlantic limestones can hardly be compared with the younger thoroughly honeycombed limestones present in Florida.

Given even a moderate unit storage capacity, many limestones should be particularly susceptible to artificial recharge because of the manner in which water moves through them. Rather than percolating slowly through tiny pores, water in limestones moves through cracks, fissures, or other channelways offering much smaller resistance to flow. Briefly, because of the network of widely distributed larger channels, the storage capacity available to one well, either a pumping well or an injection well, may be very large even though the unit percentage porosity is somewhat small.

However, the creation of storage space by overpumping will be impractical in some limestone areas traversed by large streams because the hydraulic connection between the two is excellent. Very heavy pumping of the limestone would simply draw in largely river flow and conversely, water added by artificial recharge may leak out in a matter of hours or days to the river. The degree of hydraulic continuity, and, therefore, the degree of leakage of artificially recharge water, might be appraised from observations of the water table adjacent to the river. Where areas of similar rocks are compared a steep slope would suggest a poor hydraulic connection and conversely an almost flat slope would almost certainly indicate a good hydraulic connection with the river.

Where limestone belts are isolated by boundary shales and crossed by minor streams, it should be practicable to overpump in times of greater need and recharge in times of higher rainfall. Artificial recharge in such situations might best be accomplished by damming outlets across the shale threshold in order to retain sufficient high flow for infiltration. Problems are visualized in that overpumping would dry up some springs depended upon for local supply and would lower water levels in existing production wells. In the recharge period, flooding or water logging of some areas might occur.

<u>Sandstone</u>. Sandstones, particularly the low lying Triassic sandstone, may be more suited to artificial recharge than limestone in that their permeability as a whole is only moderate. No tremendous quantity of water would be accepted by most injection wells in sandstones but, on the other hand, water accepted by the formation would tend to move out of the recharge area rather slowly.

<u>Crystalline rocks</u>. Little is known of the practicability of artificial recharge of crystalline rocks. Their storage capacity

and unit permeability is low as compared to other rocks but, given a fissured zone extending to 300 or 400 feet below the surface, useful storage capacity might be demonstrated.

Saprolite. The thick weathered rock mantle that lies above consolidated rocks south of the glaciated area is undoubtedly of primary importance in supplying water to fissures in the fresh rock at depth. Storage capacity of this material is rather high but, depending on the clay content, the permeability and specific yield may be low. The question then arises as to whether it might be more effective to flood a saprolite surface repeatedly rather than to try to gain storage by injection wells that penetrate fresh rock at some depth. Such flooding might be accomplished by constructing distributaries from large streams and rivers that would skim off a portion of high flows, which action, in a sense, would also contribute to flood control, much as natural flooding of flood plains also tends to reduce flood flow peaks. Diversions might also be accomplished by canals or pipelines that would carry water by gravity flow alone or by pumping from near or somewhat distant stream sources. Techniques for recharge by spreading have been worked out in great detail in our western states. Elsewhere such practices extend back to the time of Christ or perhaps earlier times.

MECHANICS OF ARTIFICIAL RECHARGE

Artificial recharge through injection wells cannot always be accomplished with ease. Clogging in sandy sediments is common due to presence of turbidity or gaseous bubbles in the recharge water, to sand packing, to formation of precipitates due to pressure changes or to chemical incompatibility of the injection water and the formational water. These problems are being studied and we may expect to learn much more of the limiting conditions under which well injection may be practiced and solutions to some of the common problems.

At the moment, agitation of the well in the critical entrance-exit screen area is perhaps the only method attempted to restore an injection well to reasonable efficiency. Limited dosage with certain chemical compounds may be found to be effective in some types of clogging.

The use of abandoned quarries in artificial recharge may offer an effective method of introducing water underground in some few instances. Where a quarry is located in a favorable storage area and not greatly distant from a source of otherwise wasted water, it may function as a gigantic injection well, accepting water through fissures in the walls and floor.

Raising ground-water levels where a series of broad terraces are sandy and increasing bank storage would be helpful in not only providing water for wells on the terraces, but might also be promoted as a source of supplemental water to augment low flow. However, effectiveness of dams for promoting bank storage will vary greatly depending on the geology of the area adjacent to the reservoir. Where the rocks are very permeable, "leakage" downstream around the dam may tend to dissipate most of the gain unless a definite hydraulic gradient towards a pumping well field is established. Such a dam may be a practicable step in providing more water to a well field on a year around basis but might not do much to salvage wasted high flow.

A dam anchored in consolidated or unconsolidated rock of rather low permeability would result in slow lateral movement of water through that material and in general would not be expected to be very effective with respect to increasing ground-water supplies. In this environment a low dam would be more useful in raising the river level appreciably in an upstream location in a high flow period to permit canalization of excess water to a lower infiltration ground downstream some distance back from the river.

The practices outlined above might be closely coordinated with flood control measures, in particular with reference to small dams.

The volumes of water that might be considered in this concept should be large enough to consider for low flow augmentation as well as in terms of municipal and industrial supplies.

RECHARGE USING TREATED SEWAGE EFFLUENT

There were 1,300 systems in the United States in 1967 in which treated sewage effluent is used in irrigation (25). About two-thirds of these systems were used specifically for waste-water treatment and in only one-third of these systems were crop benefits the primary objective. It is estimated that 19.8 billion gallons of effluent is disposed of by irrigation annually. This practice may be considered as a type of continuous artificial recharge and is considered here from that point of view.

Sewage effluent when given secondary treatment, provides 85 or 95 percent BOD (biochemical oxygen demand) removal and 90 percent removal of suspended solids. In addition to residual waste material, secondary treatment fails to remove nitrate and phosphate, two constituents that encourage rapid algal growth in open water with attendant ill effects.

The controlled spreading or spraying of secondary treated effluent on a soil surface allows oxidation and plant and biochemical action to take place which greatly upgrades the character of that water. After percolation down to the water table the purified effluent moves laterally to springs and streams, augmenting the flow without deleterious esthetic, ecological and health effects. Regarding the use of naturally filtered and upgraded effluent, it is stated (17) that "A notable example is the widely publicized series of recreational lakes at Santee, California, which are supplied from an aquifer that is continuously recharged with treated municipal sewage." Where slow rates of percolation through a slightly clayey, sandy soil takes place, the more troublesome viruses are removed. With respect to suspended matter "suspended particles accumulate on the soil surface as water passes through the soil and these particles themselves become the filter" but "the use of coarse soils devoid of clay...should be avoided."

Effluent subjected to the "irrigation treatment" noted above should be more thoroughly acted upon than the effluent from hundreds of thousands of cesspools which presently contribute to the ground-water reservoir. In particular, in cesspool treatment there is little or no removal of nitrate.

In applying this technique to the North Atlantic States, the following conclusions may be drawn: (1) In addition to the desirability of applying water to crops from time to time there is also a fertilizing value in the effluent; (2) controlled disposal of secondary treated effluent by spreading upon the soil can upgrade that water to the point that ground-water contamination will not occur; (3) upon emergence from the ground as baseflow of streams, there will be no deleterious effect upon the quality of stream water.

To the extent that towns and smaller cities can spread their effluent on vegetated open ground rather than directly in streams, ground-water supplies will be augmented and the quality of stream water will be improved.

The use of effluent for recharging deep artesian aquifers has been mentioned above and is shown diagrammatically in figure D-12.

Factors to be taken into account before initiating any disposal plan will be much the same as those mentioned in the general section on artificial recharge. However, there is an important difference. Disposal of effluent must proceed more slowly in order that plant and soil action have ample opportunity to act upon the effluent. Too rapid movement of effluent to the water table in sandy soil and subsoil, although providing a desirable filtering action, would probably result in incomplete removal of nutrients in the effluent. Careful experimentation will be necessary to determine the proper rate of application to achieve the primary objective of nutrient removal rather than ground-water recharge. Ground-water recharge should take place, however, even under conditions of relatively light applications of effluent, because the soil would be kept near the saturation point, in which case even light summer rains will tend to percolate through to the water table instead of satisfying soil moisture requirements. Lacking plant growth and in freezing weather the efficacy of the process in the colder months of the year is open to the question.

Disposal of effluent by "irrigation" might work well enough in hard rock areas where a thick cover of only fairly permeable material overlies bedrock. Where bedrock is exposed, particularly in limestone areas, applications of effluent would tend to seep directly to the ground-water table unchanged in biochemical or physical character.

If secondary treated sewage were disposed of by a great many communities, both large and small, in the somewhat upper parts of a basin, as now practiced in the State College, Pa. area, the quality of stream water would be upgraded to the extent that less treatment would be required by some of the downstream consumers and, inasmuch as the overall quality of the stream water was improved, the critical low flow requirement would be lowered. In thus lowering the critical low flow requirement, more water would be available for use from the stream, or, conversely, less water from upstream would have to be provided to bring low flow up to the standard required for downstream dilution of contaminants.

Unfortunately, the process may be impractical for large cities except to the small extent that effluent irrigation of not-too-distant parklands, parkways, golf courses or similar areas, by spraying rather than spreading, probably could be carried out at times of water shortages. However, the process might be considered particularly applicable to Long Island communities where future demands may exceed the available ground-water supply. There much effluent is discharged to the sea and buildup of nitrate in the ground water from cesspool effluent endangers the estuarine ecological system. Here, on open-land reserves, in irrigation of golf courses, parkways and some commercial farms, steps might be taken to dispose of effluent by irrigation to the extent possible, thereby augmenting the ground-water supply, slowing down or stopping degradation of the quality of that supply as such and protecting the quality of water in estuarine fish and wildlife habitat.

Likewise, effluent from some large cities along the Fall Zone might be piped or canalized to spreading or spraying grounds on the Coastal Plain and upon infiltration to the ground, pumped back to those cities for reuse. The concept is a large one involving many millions of dollars but may not be impractical. Some additional benefits would be gained in contributions of upgraded effluent to major estuaries.

The storage of more highly treated effluent through deep injection wells is being researched at the present time on Long Island. Technical difficulties may delay large scale recharge by these means for some years.

RECHARGE OF COLD WATER

The value of cold or cool water may be significant in the development of water supplies in some instances. The temperature of ground water at moderate depth ranges from about 41°F in Maine to about 58°F in Virginia, closely approximating the average annual air temperature. At greater depths temperatures are higher, an increase of about 1° per 100 feet of depth being common.

In 1943 it was reported (26) that at Hopewell, Virginia, cold surface water was purchased from the municipality during the winter months and recharged through wells ordinarily serving a chemical plant. The cold water thus stored in the ground was pumped out in the following hot summer season and was particularly advantageous in processing operations.

In the spring of 1944 a distillery at Louisville, Kentucky recharged the underground reservoir at a rate of 1.7 mgd with cold river water (27). During recharging operations all supply wells were shut down and city (surface) water was used. In this way the large cone of depression that had been created by heavy pumping was practically filled with cold water by a combination of natural and artificial recharge. During the summer, when the city water became too warm to use in the plants, an increased and ample supply of water was thus available from the wells.

The two-fold advantage of this procedure is that more water can be pumped from storage and that it is cold.

CHAPTER VII

SUMMARY OF GROUND WATER AVAILABILITY

ESTIMATED QUANTITIES

Table D-10 is a summary of volumes of ground water available that may be developed from a practical point of view. Wells in crystalline and metamorphic rocks generally yield less than 100 gpm and are considered suitable only for domestic and rural supplies. One-fifth of the total recharge is assumed to be susceptible to development.

Wells in sandstones should have average yields of 150 gpm, as explained in a preceding section, and wells in limestone should yield about 300 gpm. Such wells will provide an economical source of water for many municipalities and industries. In most places three-fourths of the total recharge might be developed from a practical point of view.

Where streams are bordered by glacial sands and gravels, it is assumed that a total 2 mgd per linear mile of reach may be developed by wells although in many instances 10 to 20 mgd may be developed from well fields less than a mile length. Along smaller streams, wells may have yields of only a few hundred gallons a minute and total developments will be limited to a large degree by the streamflow regimen. Along the larger streams individual wells may yield from 1 to 3 mgd in many places and significantly more in fewer places.

The calculated total available recharge to wells in artesian Coastal Plain deposits has been reduced by one-third. Wells tapping artesian beds will yield up to 3 mgd. Water available from shallower smaller yield wells in the area of outcrop of artesian beds is reduced by only one-fourth due to salvage of evapotranspiration loss.

Significant development of Coastal Plain water will affect streams and rivers flowing across and along the Fall Zone. Farther inland developments of ground water will have a variable effect on streamflow. Wells in glacial deposits near streams will tend to have an immediate subtractive effect on streamflow. Pumping wells located somewhat distant from streams will, from an overall point of view, discharge much water that would otherwise percolate to streams and rivers but the effects of pumping will lag in time and the low flows of streams may not be significantly reduced.

TABLE D-10.--SUMMARY OF PRACTICAL GROUND WATER DEVELOPMENTS

	Municipal and Industrial (mgd)	Rural and Irrigation (mgd)
Basin 1		
Consolidated rocks	230	325
Glacial deposits	620	
Basin 2		
Consolidated rocks		393
Glacial deposits	640	
Basin 3		
Consolidated rocks		277
Glacial deposits	520	
Basin 4		
Consolidated rocks		160
Glacial deposits	410	
Basin 5		
Consolidated rocks		271
Glacial deposits	60	
Basin 6		
Consolidated rocks		183
Glacial deposits	480	
Basin 7		
Consolidated rocks		240
Glacial deposits	325	
Basin 8		
Consolidated rocks	275	463
Glacial deposits	1,010	
Basin 9		
Consolidated rocks		558
Glacial deposits	380	200
Basin 10		
Consolidated rocks	113	219
Glacial deposits	320	

TABLE D-10.--SUMMARY OF PRACTICAL GROUND WATER DEVELOPMENTS--continued

	Municipal and Industrial (mgd)	Rural and Irrigation (mgd)
Basin 11		
Consolidated rocks	492	493
Glacial deposits	225	
Basin 12		
Consolidated rocks	316	561
Glacial deposits	840	
Basin 13		
Glacial and coastal plain	750	
Basin 14		
Consolidated rocks	429	47
Glacial deposits	200	
Coastal plain deposits	29	
Basin 15		
Consolidated rocks	684	386
Glacial deposits	500	
Coastal plain deposits	733	
Basin 16		
Coastal plain deposits	244	
Basin 17		
Consolidated rocks	2,595	993
Glacial deposits	1,860	
Basin 18		
Consolidated rocks		80
Coastal plain deposits	793	7.4
Basin 19		
Consolidated rocks	1,597	514
Coastal plain deposits	145	24
Basin 20		
Consolidated rocks	98	170
Coastal plain deposits	81	28
Basin 21		
Consolidated rocks	757	369
Coastal plain deposits	49	21

CHAPTER VIII

RECHARGE PER SQUARE MILE AND WATER AVAILABILITY

GENERAL DISCUSSION

The recharge figures given here represent a reasonable estimate of how much of the water that reaches the water table may be salvaged by pumping. The total water availability figures represent available ground water in a static or unstressed system and are suitable only for broad planning purposes where complete development is considered.

The greatest fault inherent in using recharge rate figures in localized site studies is that the effects of induced recharge from adjacent streams under heavy pumping conditions at time of normal streamflow are not taken into account, nor perhaps more importantly, is the additional recharge indicated that might occur during periods of very high flood flows in areas where ground-water levels are sharply depressed. Failure to allow for at least some salvage of evapotranspiration loss may also lead to underestimates.

Taking the evapotranspiration factor first, the capture of that loss could be as much as 10 inches of rainfall per year--about 173 million gallons a year per square mile or $\frac{1}{2}$ mgd per square mile. However, where the water table is initially more than 20 feet below the surface, evapotranspiration salvage will probably be very much less.

The amount of induced infiltration from the main stem, from tributary streams, and from countless normally insignificant and ephemeral streams carrying wet season runoff can only be determined by site studies. On areas underlain by coarse granular sediments or greatly fissured limestone rocks it may be very large. Further, as noted above, the limit is not the direct runoff (surface runoff) in each square mile--a very considerable volume of water might be captured from streams originating many miles outside of any one site being considered.

The volume of recharge in any locality might be increased by structural measures, as discussed in the chapter on artificial recharge.

In any maximum ground-water development, storage must also be taken into account. Let us assume that the availability of ground water in any one discrete square mile is $\frac{1}{2}$ mgd (as given in table D-7). Upon pumping and lowering of the water table, at least a little evapotranspiration loss is salvaged. Infiltration from streams in the area, particularly during the wet season, might raise the water flowing to wells to 2 mgd. However, the pumps are discharging 5 mgd. In this case water is being taken from storage as brought out in the discussion on "Use of Ground Storage." In granular sediments available storage water may be 41.8 million gallons for every foot the water is lowered in one square mile. In the shattered limestones, in Virginia, Maryland, and Pennsylvania each square mile of saturated rock 1 foot thick contains over 8 million gallons of water. Lowering the water level 100 feet in a one square mile area would then yield 800 million gallons of water.

The problem may not be the volume of storage reserve but rather, the difficulty of making up the difference between normal recharge and the volume taken from storage. In shattered limestones the cone of depression may spread out many miles, thus drawing water into the well from 20 or 30 or more squre miles, but in granular sediments there will be far greater dependence on local precipitation formerly lost as direct runoff and contributions from streams crossing or adjacent to the well field area.

"Normal" recharge is particularly inapplicable in glacial sediments and probably to a lesser degree to hard rock aquifers. In the preceding discussion of glacial aquifers an arbitrary figure of water availability was based on induced recharge from the major streams and tributaries. Even where little or no induced recharge is possible, some capture of evapotranspiration loss (table D-2) and normally rejected recharge must be considered. In many places the effect upon streamflow would be a limiting factor. This topic is discussed further in the section dealing with ground storage.

In any site, then, it may be found that recharge per square mile is not the critical factor in calculating ground-water availability. Commonly, use of that figure may result in underestimating what is available at a particular site. On the other hand in the crystalline rock areas the permeability of the mass may be so low that capture of the total available recharge and intermittent depletion of storage would be possible only by a grid of closely spaced wells, in which case costs would be prohibitive.

Consumptive use should also be considered. Actual consumption may be less than 10 percent of water withdrawn (28). However, the water returned to the system may be of poor quality unless highly treated by conventional methods or by "irrigation," as discussed elsewhere in this report.

In deciding how much water is available from a closely spaced group of wells then, it is clear that average available recharge figures (derived from base flow data) is commonly inapplicable to site situations. As discussed in preceding chapters of this text, high yields can be developed from gravels, limestones, and sandstones. The extent of the formation must then be considered, over how wide an area and from what sources it will receive recharge. It must also be determined that recharge in adjacent areas will move to a heavily pumped well field quickly or slowly. Finally, how much storage is available at the well field and in adjacent areas for use at time of negligible precipitation? Briefly, costs of well construction, geology, the geometry of the formations, transmissivity, coefficient of storage and specific yield and flow characteristics of adjacent streams are all factors in assessing ground water availability at any one site.

CHAPTER IX

GROUND STORAGE

AVAILABILITY

It has been brought out above that in many areas it is possible to discharge water from the ground for a limited period, as during the dry season, without subtracting significantly from streamflow. The ground water produced will be an addition to the total supply at that limited but highly critical period of time. The applicability of this concept is dependent on geohydrology, cost of water produced and volumes of ground water available relative to the flow of the stream.

As noted in figure D-3 a well close to a stream will deliver stream water in largest part and there is no gain in overall water availability, but a well distant from a stream will discharge a significant volume of water from storage at time of low streamflow, as shown in figure D-4B. The volume of water taken from storage is a measure of the gain in total water availability at the time of low flow--in this instance 0.7 mgd. Note that even in this example there is some recycling of stream water. In wells at a greater distance from the stream recycling might be essentially nil. Closer to the stream the amount of recycling will increase.

The point is made here, of course, that development of ground storage may be practicable even where there <u>is</u> a fair hydraulic connection with the stream network, as a consequence of which some recycling takes place and stream flows <u>are</u> affected to an appreciable degree.

It may also be noted that the water from ground storage (and water infiltrating from the stream) in sandy sediments will ordinarily be of high quality whereas, at time of low streamflow, the stream water may be of especially poor quality. Maximum utilization of underground storage at such time may be desirable entirely on the basis of quality improvement of the total supply, either in providing the consumer with the best quality water available or in reducing costs of treatment plant operations.

GROUND STORAGE FOR LOW FLOW AUGMENTATION

Glacial deposits. In many places glacial deposits are unsuitable for low flow augmentation of streams. Most of the important glacial aquifers occur as relatively narrow bands along a stream and have an easy hydraulic connection with the stream. Water in ground storage may be present in significant volume, but drawing upon that storage will induce infiltration from the stream (fig. D-3B) and, depending upon the amount of recycling, costs may rise sharply.

On the other hand, some terraces of glacial origin flanking some streams are as much as three miles wide. Wells established, say, one-fourth mile or more back from the stream may induce very little stream infiltration (fig. D-4B). The probable difficulty here is that (1) the thickness of saturated material may decrease sharply with distance from the river and (2) sustained yields of wells may commonly be less, perhaps much less, than 1,000 gpm, (3) most wide terraces are located along the lower main stem where development of even 5 or 10 mgd from ground storage in a few places may be insignificant relative to the flow of the river.

There are a few other situations where development of ground storage from glacial deposits might be practicable. Where a stream in a valley filled with glacial deposits contributes only a small flow to a larger stream, it may be worthwhile to exhaust a fairly large volume of storage in the small valley, even though the small stream in that valley is dried up. The ecological implications of such action are, of course, apparent and may function as a constraint.

Abandoned glacial stream channels, some many miles in length and underlain by considerable thicknesses of saturated sand and gravel are known. These mark the former courses of major rivers but now support only a brook or no through drainage at all. These channel deposits may offer real possibilities for low flow augmentation in a few places. Although very large volumes of water per unit area may be available, as discussed in the section dealing with glacial deposits, costs will determine whether or not development is practicable. Where augmentation of somewhat smaller streams and rivers are concerned, development may well be practicable.

Coastal Plain deposits. Water from undeveloped artesian aquifers might lend itself to low flow augmentation in a few places. Large quantities of water at very low cost can generally be developed from artesian beds without inducing immediate significant inflow from surface streams but the addition of several tens of millions of gallons of water a day to major rivers east of the Fall Line may not be particularly helpful. Rather, augmentation might better be considered for isolated estuarine inlets or bays where shell fish grounds, bathing beaches or other facilities are endangered by polluted water. For such purposes saline ground water may be entirely acceptable, that is, if marine life is not dependent on a particular salinity level. Saline ground water may be too saline or not saline enough in some circumstances.

Consolidated rocks. Very large quantities of water are available from storage in the shattered limestones present in the Appalachian Valley. Assuming a storage factor of 4 percent, 1 square mile of saturated carbonate rock 1 foot thick contains about 8.3 million gallons of water in storage (27,878,400 sq. ft. x 4% x 7.48 gal. = 8,339,900 gal.). Lowering the water level 100 feet over a one square mile area would then yield 830 million gallons.

Low flow augmentation of some Appalachian streams would not require that all the water be delivered at one point, as is provided by surface structures. A series of discharging wells along a many-mile reach of river would be quite satisfactory for the purpose and would bring pipeline costs to a minimum. Thus, if low flow augmentation of South Fork of Shenandoah River at Waynesboro were desired, capture of 100 feet of water in ground storage in a zone 2 miles wide for 13 miles upstream might furnish 21,000 million gallons. Discharged over a period of 90 days this becomes 240 mgd or 370 cfs. It might be assumed that 16" x 10" wells 300 feet deep could produce 2,000 gpm at a total cost of $47,000 per well, or even less. On this basis annual amortization at 5-1/8 percent interest maintenance costs would be about $3,800 per well. Cost of water per thousand gallons would be less than 6 cents if wells were operating all year around. Because they do function only ¼ of the year, the actual cost of water would be about 35¢ a thousand gallons.

However, the plan sketched out above may be impractical along the South Fork as well as along many of the rivers in the carbonate rock areas due to the recycling of water that would occur if wells were located near the river. Alternatively it may be quite possible to draw from storage from wells located back from the river where the hydraulic gradient toward the river is relatively high.

Following the line of thinking expressed in the above paragraph, perhaps a more certain approach might be made by considering pumping from those parts of a basin that are separated from the main stem by a geologic barrier (fig. D-13). In such instances wells could be somewhat closely spaced, higher yields obtained by utilizing maximum drawdown and costs much lower. Pipeline would

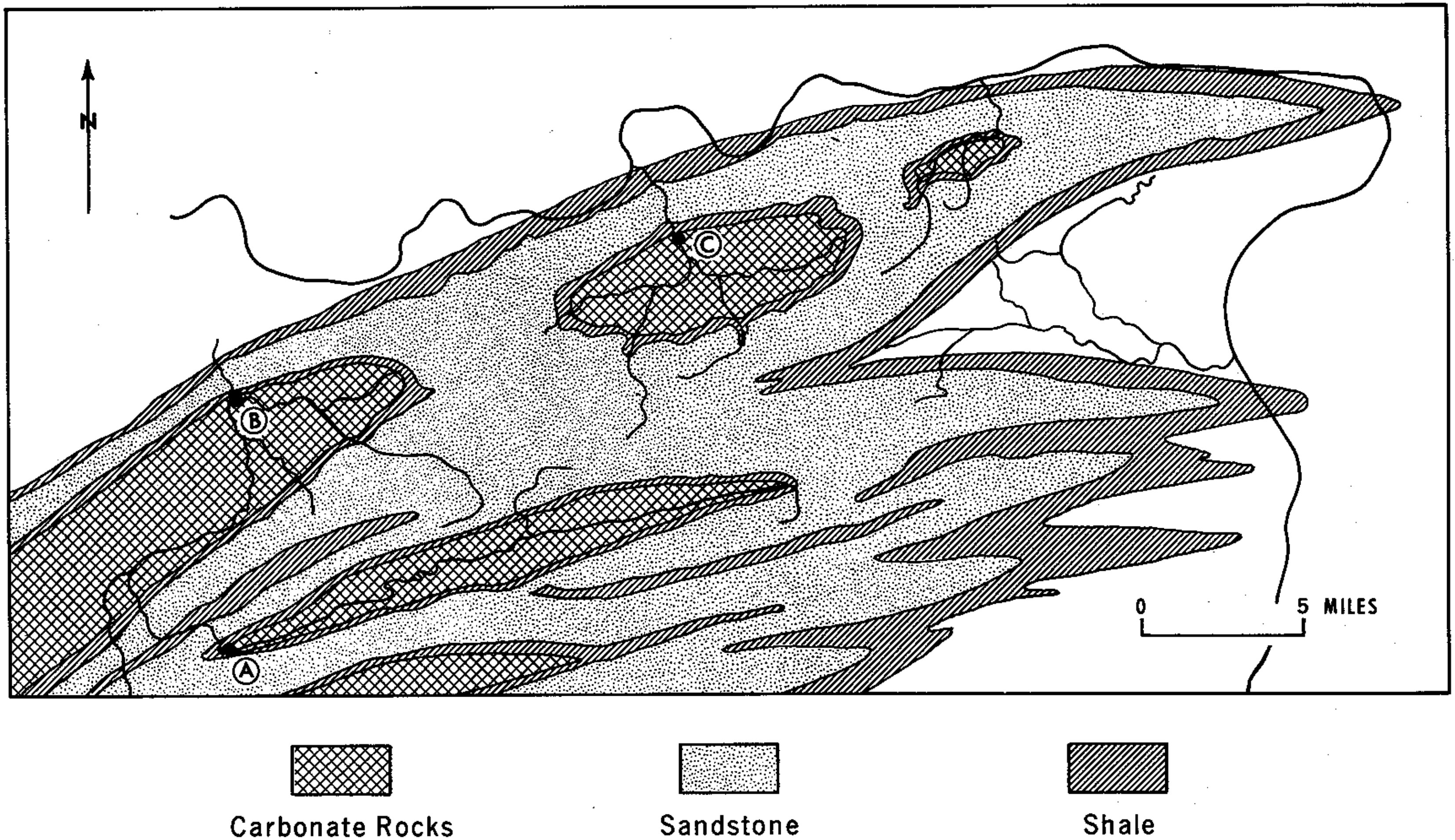


Figure D-13.--Sketch map showing one type of geological environment where advantage might be taken of underground storage. At times of drought and very low or lack of flow of streams issuing from the carbonate rock basins shown, pumping from storage may be possible for low flow augmentation of the main stem. Very large drilled wells or larger diameter shafts equipped with pumps located at A, B, and C deliver water across (north of) the shale threshold. Lowering the water table 50 feet throughout the three large carbonate rock basins would provide about 700 cfs for 90 days, assuming a 4% storage capacity in the carbonate rock (100 sq. mi. x 8.36 mgd/ft x 50 ft x $1\frac{1}{2}$ ÷ 90 days). Slow increments from adjacent sandstone areas are not included. Tunneling through to B and C from the north might be feasible.

be necessary, however, to bring the water pumped over the ground water divide (preferably a divide due to the presence of a belt of shale) but not to the main stem itself.

More or less complete compartmentation of ground-water storage below river level should be present in a great many places in the Appalachian Valley.

In granular sediments, available storage water (specific yield) of the mass may be taken as 20 percent or 41.8 million gallons for every foot the water is (27,378,400 sq. ft. x 1 ft. x 7.48 gal. x 20%) lowered in one square mile. Here it is readily apparent then that the problem may not be the volume of water in many underground reservoirs, but rather how to get it out at a reasonable cost and how to recharge the reservoirs when they become depleted. Extracting the 41.8 million gallons of storage in a one-foot saturated thickness of glacial sands one mile square in a 90-day period would require a daily discharge .46 mgd--something that could be accomplished rather inexpensively in many places. Extracting 20, 30 or 80 times that volume (depending on the thickness of the saturated section) would probably be mechanically, hydrologically and financially difficult.

In comparing this alternative with costs of surface water impoundments, capital costs or total annual costs are properly used for comparison inasmuch as water is released from a surface impoundment also during the assumed 90-day period.

Additional cost benefits assumed for a surface impoundment where recreation facilities (boating, fishing, etc.) are provided may be offset by the fact that the ground-water system takes almost no land out of normal production, evapotranspiration losses--high in a surface impoundment--are much less and water from a carbonate rock ground-water reservoir, although hard, would be sediment free.

A deal of research is needed in this area of thinking. Recalling the ground-water discharge at the Friedensville Mine, it is clear that only by imposing a stress on the ground-water system will the potentialities and practicalities of optimum utilization of ground storage be provided. Such "studies" will necessarily be "research" into construction of large-diameter deep wells intended to produce much more than a few million gallons a day, the discharge of large volumes of water from discrete sub-basins, and the evaluation of aquifer response, particularly in observation wells. In view of the inability of ever determining all the geological framework beforehand, the final answer will only be obtained through field operations.

Sandstone terrane is somewhat better suited for depletion of storage without probability of recycling but the large quantities of water available from the carbonate rocks cannot be developed. Costs for low flow augmentation from wells ranging up to 1 mgd each might be prohibitive in many places. Low flow augmentation from wells in shale or crystalline rocks should not be considered.

GROUND STORAGE FOR INDUSTRIAL AND MUNICIPAL SUPPLY

In utilization of ground-water supplies by municipalities and industries relatively little thought is given to full development of storage potential. Rather, and justifiably so, attention is ordinarily focused on locating a well anywhere that a sustained yield can be obtained, the closer to the point of use the better. Putting the same thought in a different context, considerable thinking and expertise has gone into evaluating the sustained yield of wells that are dependent in large part on river or stream infiltration.

Most installations function largely by skimming the top of the aquifer, pumping something less than the average annual recharge increment and relying only a little on the storage present in the aquifer as a mass--or, as noted, depend to a greater or less degree upon infiltration from a river. Thus, in the North Atlantic Region tremendous volumes of storage water remain untapped (fig. D-13).

It is too much to expect a city, an industry, or a water district to concern itself with this fact. Rather, it is in the province of the broad planner to seek out, identify and quantify such resources and by whatever means are available, costs permitting, bring these reservoirs into the overall water supply system.

The potential for utilizing ground storage for low flow augmentation is probably limited to relatively few areas, as noted, because of the large quantities required, limitations of yields of wells and costs. These restraints are not as applicable to city and industry needs because those needs are one or two magnitudes smaller and because higher costs can be accepted.

Therefore, from a broad planning view, can a series of well fields be established that will take full advantage of ground storage potential to supply growing needs of many cities and industries by much the same financial and political means as surface impoundments are brought into existence.

To plan in this manner requires studies of more limited segments of basins and subbasins than has been attempted in this study but it must be on a higher level than the usual site study.

With ground and surface potential reasonably well quantified, it will then be possible to choose reasonable alternatives. One or a series of well fields at some distance from the points of need might negate the necessity of a surface impoundment as sole supply, or might merely provide the extra clean water required during a drought period when streams are at their highest level of pollution, in effect, accomplishing better what is hoped to be accomplished by low flow dilution. In proposed loop systems, considered to be the answer to distribution and supply in the more heavily settled areas, it would be possible to make full utilization of ground storage along and near the loop even though the loop were based upon a very large surface-water supply.

Depleting a ground-water reservoir greatly may result in a deficiency not made up by recharge in the following year. As noted elsewhere in this report, normal recharge per square mile may be a million gallons a day, or even much less. Hence, measures may be needed to refill the reservoir--conventional artifical recharge as outlined in a preceding chapter, controlled disposal of secondary treated effluent, or following a pump-storage concept, pumping recharge water from a river during times of high flow, perhaps using the same pipeline that delivers water during the dry season.

VOLUMES AVAILABLE

In assessing the perennial yield of wells in the North Atlantic Region, the average recharge water was estimated and the yields of individual wells was estimated at 100 feet of drawdown. In withdrawing water from the ground from properly spaced wells in consolidated rocks--in each square mile only enough wells to take up the average recharge--the water level is not greatly depressed relative to the total depth of the well. In most instances there will be from 100 to 250 feet of hole in saturated formation below the pump intake. The storage water could be withdrawn by lengthening the pump column appropriately, thereby making available greater drawdown.

The overall storage factor for void space in the consolidated rocks considered here is taken to be about 2 percent. If water levels were lowered 100 feet, one square mile of aquifer would yield 418 million gallons. It is further assumed in these calculations that only one-fourth of volume is recoverable due to lack of free intercommunication of all parts of a block of ground in which relatively few wells are located. Such discounting is also made in recognition of the fact that if the storage were to be used as a supplementary supply during times of critical low flow, wells located near streams and rivers would only be pumped lightly in order to minimize infiltration from those streams and rivers.

For easy calculating purposes it may be assumed that 100 million gallons of ground-water storage per square mile is available for emergency use from the more favorable consolidated rocks, that is, limestones and sandstones. These quantities are listed in table D-10. Storage water in the plateau sandstones is not counted.

The storage in crystalline rocks, although very large in the aggregate, is not given because that water is available only to low yield wells. It will suffice to say that, in most instances, there should be ample storage water available by lowering pump intakes to tide over in periods of excessive drought where wells in crystalline rocks supply villages and small industrial needs

In calculating the maximum volume of water available from artesian aquifers in the Coastal Plain, it was assumed that water levels would be drawn down nearly to the top of the formation. Additional drawdown would uncover the well screens, which is considered undesirable. Therefore, storage in these formations is not listed as not available inasmuch as water available on a sustained basis is already given in table D-10.

However, as noted in a preceding section, considerable storage is available in the outcrop section of the artesian aquifers. Inasmuch as water from the outcrop areas will be available from relatively low yield wells, not generally exceeding 200 gpm, probably not more than 5 percent of the estimated available storage would be drawn upon. The figures given in table D-11 are 5 percent of the calculated total storage.

Calculations on the potential of the water table formations of Long Island, New Jersey, and Delmarva Peninsula are based on reducing storage sharply to induce maximum infiltration and minimum evapotranspiration. Hence, no available storage is shown under conditions of maximum development.

In glacial deposits, the volume of storage is relatively small in most places and much of it may be needed to carry over sustained discharge of wells in periods of low precipitation without excessive reliance upon river infiltration. There are a few places where unused storage might be drawn upon, in some parts of the lower Connecticut basin west of the trap ridges, in abandoned gravel filled stream channels in Maine and elsewhere, in a few broad areas, as between Albany and Lake Champlain and north of the Adirondacks, and elsewhere. The potential of most of these can be estimated only after site studies and hence the unused storage capabilities of glacial sediments are not listed. However, as pointed out in a previous section, the capability of coarse granular deposits to store and yield water may be as much as 2 billion gallons per square mile where the water level can be lowered 50 feet. Hence, the potential of even quite small deposits should not be ignored in a study of total water resources.

TABLE D-11.--UNUSED GROUND-WATER STORAGE

Basin	Aquifer	Volume (billion gallons)
1	Consolidated rock	620
8	Consolidated rock	1,645
11	Consolidated rock	2,645
12	Consolidated rock	1,515
14	Consolidated rock	1,145
	Sand and gravel	1.25
15	Consolidated rock	1,825
	Sand and gravel	9.1
16	Sand and gravel	21.5
17	Consolidated rock	4,650
18	Sand and gravel	8.03
19	Consolidated rock	4,070
	Sand and gravel	1.6
20	Consolidated rock	260
	Sand and gravel	1.4
21	Consolidated rock	2,220
	Sand and gravel	1.35

CHAPTER X

CONJUNCTIVE SUPPLIES

DUAL WATER SOURCES

It should hardly be necessary to point out that in supplying a demand, that supply need not be developed from only one source. If in supplying a specific municipality or industrial plant, a near source of ground water will furnish a significant fraction of the total demand, considerable economy might be achieved in that the major (or minor) surface supply can be scaled down. The argument will fail only if it is not possible, because of topographic or other conditions, to build a smaller surface impoundment at a reasonable cost in terms of water cost per thousand gallons. Some cities along the Fall Line, for instance, might develop several tens of millions of gallons a day of high quality ground water to supplement larger surface water supplies from upstream. Sustained discharge from any one well field tapping artesian beds might be somewhat low in some areas. Yet during critical low flow periods wells might be "over pumped" to yield 30, 40 or 50 mgd, thereby providing the extra makeup water needed for brief periods.

INTERIM GROUND WATER SUPPLY

Let us examine a growing area, presently supplied with sufficient water but which may need additional water in the future, with the understanding that a significant ground reservoir exists and that utilization of that reservoir is an alternative to drawing from a small or moderate sized surface impoundment. It is further assumed that although ground water is available, there may not be enough to meet the projected demand for, say, year 2020. However, let it be assumed that the supply is found sufficient for the area until year 2000. At that time it may be found that (1) high-cost surface impoundments will be needed or (2) projected demands have not materialized and additional supplies are not needed, or (3) as a result of aggressive and imaginative development of ground-water supplies and experience in management of the ground-surface system as a whole, including reuse techniques and artificial recharge, sufficient additional ground water <u>can</u> be provided at relatively low cost and minimum alteration of the environment.

In the event that surface water impoundments do have to be constructed in year 2000, and even if those impoundments are built to supply the entire water demand, no loss will have been incurred in having previously constructed (temporary) ground-water installations. The cost of water from the ground will have been considerably less than the cost of furnishing surface water and in the two decades of reliance upon ground water a saving quite possibly great enough to write off the entire cost of the well installations will have been made. If land for the surface water impoundment is held by the responsible political subdivision during the two decades of presumed idleness, there would be a loss on the interest of that investment and a loss of taxes and productivity, but a large saving would be gained in not carrying amortization and maintenance costs on the impoundment eventually required. Further, with well installation costs written off, the area would now have a large "free" auxiliary system[2/] that would be highly useful in permitting better regulation of the surface reservoirs and for emergencies such as atomic dust pollution (water from Coastal Plain artesian wells, particularly), city wide fires or unanticipated failures of the surface water system.

CHAPTER XI

NEED OF CRITICAL DATA

GENERAL DISCUSSION

Comments made by a concerned public official (29) after critical reading of the Preliminary Issue of this report are, in part, as follows.

"As the technology for ground-water development (including recharge) improves, and we are confident that such is inevitable, the probabilities are quite high that present day assumptions, which limit the reliance of ground water as a supply source, will be significantly increased."

Further, with reference to "the optimum development of recharge techniques as a device for improving low flow conditions.... We are of the opinion that the cost difference between the two approaches (surface versus ground reservoirs) is large enough to warrant a more intensive enhancement of ground-water technology (i.e., research and data collection), and we recommend that this be expressed in Appendix D of the NAR study."

These remarks, although encouraging from the writer's point of view, touch upon a need that exists in the ground-water discipline. Many topics dealing with occurrence and management of underground water have been discussed in the foregoing section of this report. Many statements made are factual, others are interpretations based on facts, and many statements are presentations

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2/ Amortization charges made in cost computations quoted allow for complete replacement every 25 years.

of concepts that stem from specific knowledge of hydrologic behavior in isolated instances. The discussion of the implications of the Friedensville Mine pumping and the suggested application of data pertaining to disposal of treated effluent, are good examples of concepts presented. These concepts may well be of greater import than the simple facts assembled for this study even though some of these concepts may be based on unique occurrences.

Granting the above conclusion, it may be asked why reasonable points of view in the field of ground water cannot be documented in more detail. Ground water has been used as one source of large supplies for some years now and it might appear that ample "evidence" should be available to confirm nearly all thoughtful conclusions.

What do ground-water data consist of? In largest part, basic information consists of well records of varying degrees of completeness obtained from developers who have drilled here and there in places where they hoped to find water. The great mass of available data in the field of ground-water hydrology is, therefore, rather much hit-or-miss material from which the hydrologist or developer may or may not glean critical information pointing to the practicalities of full use of ground water and its ultimate interrelationship with precipitation runoff, natural recharge, evapotranspiration, pump discharge, consumptive use, streamflow, and induced or artificial recharge. It is a rare occasion indeed when the seeker after knowledge in the field, whether it be developer or hydrologist, has time and funds to drill test holes in critical areas, and to make more than brief pumping tests--steps which enable him to evaluate the interrelationship in a dynamic situation or the sum total of ground water available under the constraints applicable to the study.

Contrasted with ground-water data, information on the availability of surface water appears to be more adequate for most purposes. The reason for this apparent sufficiency can be easily understood. Stream-gaging stations are established on essentially every major river in the North Atlantic Region--and elsewhere in the United States--and from decades of records already at hand, firm statements may be made of probabilities inherent in streamflow characteristics. Millions of dollars have been spent in obtaining these records and millions more will justifiably continue to be spent.

Critical data on ground water, largely those gained only by construction of physical structures (test holes, pumped wells, experimental recharge facilities) are meager and the hard data needed to implement useful concepts, or even points of view, are available largely by chance.

It is concluded, therefore, that if more funds were expended in the discipline of ground-water hydrology for the specific purpose of test drilling and pumping in critical areas and analyzing the resultant stress on the dynamic system, alternatives for development of water supplies in the NAR could be presented with greater confidence.

CHAPTER XII

ENVIRONMENTAL EFFECTS

Any change in the ground-surface water system may be expected to result in changes in the total environment. It is submitted here that the effects of ground-water withdrawal in the North Atlantic Region will, except in special situations, create insignificant alterations in ecological conditions, not only in plant growth and wildlife habitat but in human habitat as well.

THE NEW JERSEY PINE BARRENS

Perhaps the greatest adverse effect that might be experienced is the draining of swamps and boggy ground by nearby withdrawals of ground-water where these areas function as wildfowl flyways and fish spawning grounds. However, most of the great coastal swamps from Virginia to the mouth of the Hudson lie in areas where surficial formations yield only small quantities of water and development of large supplies of ground water from them is impractical. Hence, most of those swamps will not be endangered by ground-water withdrawals. Degradation or loss of this swampy ground might more likely result from filling for housing sites, from building of swimming beaches or from waste-disposal activities of nearby or distant communities.

The New Jersey Pine Barrens and a few similar more or less soggy inland areas along the coast are subject to change owing to ground-water withdrawal in those areas. There the surficial deposits are thick, they contain tremendous quantities of water in storage, and are subject to rapid recharge by rainfall. In view of the projected demands of the Megalopolis, it is certain that this source of ground-water supply will be kept in mind by future planners. Ecological effects of lowering the shallow water table a few feet throughout and tens of feet around centers of pumping would occur, but what these effects might be can be best decided by experts in the field. Presumably the unique trash timber assemblage might give way to stands of higher grade forest, although it may be noted that somewhat similar low-grade forest cover is present on Long Island where the ground-water table lies deep. Ground-water in the Pine Barrens would tend to improve in quality with lowering of the water table in that much forest litter, now lying in wet depressions, would contribute much less plant acid to the ground-water reservoir. Some small streams would probably vanish and larger streams would have a diminished flow. Care in siting wells would preclude inland movement of saline water.

The disposal of secondary treated sewage in the Pine Barens area would likewise produce an environmental response. It seems likely that water levels would have to be lowered at least a few feet for the operation to function effectively, in which case the changes already noted would occur. The nutrient added by disposal of the effluent would undoubtedly promote even more rapid growth of quality timber and other plant cover. If treated sewage were disposed of by "irrigation" on the Pine Barrens, much of it might ultimately leave that area as ground-water runoff of high quality (low nutrient content). With lesser volumes of treated sewage dumped into upper Delaware River upon adoption of the practice, the quality of Bay waters would then be upgraded and an improvement in the fish, shellfish, and wildlife environment in the Bay would follow as well as an improvement in the potential for water contact sports. However, the quality of water in streams within the Pine Barrens would be degraded somewhat if the sewage effluents were high in chloride, metallic constituents or other nondegradable constituents.

Not at all incidentally, the practice of land disposal of effluent by irrigation anywhere should, if carried out properly, tend to improve the quality of land utilized as well as to promote ground-water recharge and to upgrade river water quality. From a larger point of view--land being available--green strips could be established for intermittent disposal use. Strips lying "fallow" for a period of weeks might be usable as hiking grounds, for bird watching or other outdoor activities. The green strips set aside could also provide pleasant visual relief in some more urbanized areas, either as such or as screens for unsightly areas.

CRANBERRY BOGS

Cranberry bogs along the New England Coast would probably be endangered by nearby ground-water withdrawals. Drying up of some bogs might occur and, depending on their location, inland movement of salt water might endanger others. Site studies would be necessary to determine where ground-water withdrawals might be made without adversely affecting the bogs.

Boggy or swampy ground in the inland locations occur in a great variety of situations. Here, too, site studies will be necessary to determine whether or not such areas would be affected by nearby pumping and planners will necessarily decide whether possible lowering of the water table is unlikely. It should be noted that little factual information is available on the permeability of swamp deposits and their susceptibility to vertical drainage.

FOREST AND GRASSLAND

By and large, the water table in the North Atlantic States is close to the surface only along streams and lies 10 or more feet below the surface elsewhere. Lowering the water table in the interfluve areas will bring about only subtle environmental changes, if any. Plant growth is seemingly supported by soil moisture to a very large extent in the temperate North Atlantic Region (2). Soil moisture, in turn, is a function of the rainfall and receptivity of the soil. Few, if any mesophytic species depend upon water from the water table or the capillary fringe. No doubt some mesophytic species obtain some water from below the zone of soil moisture, but they are not dependent upon that auxiliary source. With lowering of the water table such plants and trees may grow more slowly than previously, but their disappearance should not be expected. Where roots do not follow a gradually declining water table, transpiration will decrease, and that much more water will remain in the ground-water reservoir (4, 5).

LOW FLOW AUGMENTATION

Withdrawal of large quantities of ground-water from storage during the dry months for low flow augmentation, as discussed in the chapter entitled "Use of Ground Storage," should have a beneficial effect upon the ecology. As noted above, the lowering of the water table in interfluve areas in the North Atlantic Region will have little effect upon the plant and tree cover, although a few brooks and small swampy areas may be adversely effected. On the other hand, the addition of ground-water from storage to essentially small streams in the dry season may be critical in sustaining fish and wildlife in the upper reaches, even though the primary purpose of pumping ground-water may be to supply a different type of demand farther downstream. However, such stabilization of the regime may not be desirable for some species.

If large ground-water withdrawals are made in the dry season, the high stream flows in the following wet season will be reduced slightly as the depleted ground-water reservoir is recharged. In some instances this reduction might be significant with respect to small streams, but in no case could such increased infiltration be thought of as seriously diminishing a cleansing flood flow along a large river.

ARTIFICIAL RECHARGE

Diversion of some higher flows for artificial recharge would likewise have only a minor effect upon streamflow in most instances. Further, in bringing such water upon the land, the addition of suspended and dissolved elements in the river water would tend to improve the fertility of the soil. The low-flow augmentation and subsequent reduction of high flows sketched out above, could hardly have an observable effect upon marine life in thegreat estuaries along the Atlantic seaboard in view of the quantities of water involved. The practice would tend to stabilize the ecological environment but could hardly be promoted on that basis alone.

CONCLUSIONS

As stated initially, any change in the ground-surface water system (and in any other natural system) will produce an environmental reaction. Where additional water <u>must</u> be produced, changes may occur upon development of additional water from any source or by whatever means. Planners may then decide that certain small or large changes must be accepted even though they modify the environment appreciably or because the effect is negligible or, conversely, that certain effects simply cannot be tolerated. Alternative action to be taken where profound environmental changes are anticipated, that is, shifting the water demand elsewhere, lies in the socio-political field and is not properly dealt with in this paper.

CHAPTER XIII

CONCLUSIONS

SUMMARY OF GROUND WATER AVAILABILITY

It has been shown that large volumes of ground water, from a few million to several tens of millions of gallons a day per well field, are available in the North Atlantic Region in much of the Coastal Plain; in belts of sandstone and carbonate rock (limestone and dolomite), particularly where these have been folded and faulted; and in glacial sand and gravel beds, generally adjacent to rivers and large streams (D-1A, D-1B, and fig. D-9). The average yield of wells in sandstone and carbonate rock is respectively, about 150 and 300 gpm. In favorable locations, wells in Coastal Plain sediments may yield in excess of 2,000 gpm and many wells in glacial deposits yield more than 700 gpm.

Smaller quantities of ground water, generally less than 75 gpm, are available from wells throughout the region in areas underlain by crystalline rocks and shale. Development in any one place is generally limited to not much more than 1 million gallons a day. In addition to supplying rural inhabitants with water, relatively low yield wells provide adequate water for small industries and municipalities in many places.

The total volume of ground water available in each basin is estimated and shown in appropriate tables. The amounts that might be recovered by wells for industrial and municipal purposes is also estimated.

The quality of ground water is generally good. In carbonate rock areas the water is hard, in glacial sediments undesirable amounts of iron or manganese are not uncommonly present and, near the sea, wells in Coastal Plain sediments yield water that is too high in chloride and other constituents to be useful for most purposes.

Pumping of ground water may subtract nearly an equal volume of water from the flow of nearby streams but, with proper management, wells in some areas may be located that draw wholly or partly upon underground storage during low flow periods. Pumping from such wells will thus add to total water availability at time of low flow. The resultant deficiency in underground storage will be made up by normal recharge during the succeeding wet months or, if not, artificial recharge techniques may be employed. Artificial recharge measures may consist of inhibiting local runoff, spreading a part of the high flow of streams, utilization of secondary treated effluent by "irrigation," or other procedures.

In some, perhaps relatively few, places, the volume of underground storage may be large enough and cost of discharging that water by wells low enough so that it is practicable to utilize ground water for low-flow augmentation of streams or as significant supplements to water users ordinarily depending on surface supplies.

PART II

THE COST OF GROUND WATER

CHAPTER I

INTRODUCTION

PURPOSE

In the North Atlantic Region water resources study carried out under the leadership of the U.S. Army Corps of Engineers, it became the responsibility of the Geological Survey, as a participating member of the group, to evaluate not only the ground-water resources in the region but also the cost of supplying water from wells. Part II of this paper deals with that phase of the study.

As discussed in detail below, the elements that must be considered in arriving at costs are (a) the probable yield of wells in various geologic environments, (b) the cost of drilling and equipping the well for production, (c) the spatial distribution of wells relative to volume of recharge per square mile or other source of recharge, (d) the cost of interconnecting pipeline in multiple well developments, and (e) amortization of capital costs and assignment of maintenance and pumping costs, all of which refer to a series of calculations of cost of water per thousand gallons delivered at the wellhead or at either end of a well field consisting of two to as many as 40 wells.

Additionally, it is shown that variations in capital costs, even rather large variations, will result in only very small changes in cost of water to the consumer, that is, in the cost per thousand gallons. On that account it appears that most "economies" in well field construction--a minimum of test drilling or skimping on the amount or quality of equipment--will prove costly in the long run. The subject is touched upon in the section titled "Average Yield and the Developer" and will be dealt with in more detail below.

LIMITATIONS OF COST ESTIMATES

The cost figures are analyzed and based on generalized conditions and cannot be applied to particular site situations in view of several factors other than recharge per square mile and average yields of wells upon which these cost calculations are based. These factors are (a) susceptibility of recharge by streams originating outside the well field, (b) ground water percolating into the well field from outside the block of ground assumed to be the recharge area or, conversely, failure to capture all the recharge in that assumed area, (c) a greater rate of annual recharge when water levels are depressed by pumping, (d) smaller ground water outflows to the stream system when the water table gradients to the streams are lowered as a consequence of pumping from wells, (e) capture of evapotranspiration in and around an operating well field, (f) possible reuse of water pumped and (g) very great differences in the permeability of any one rock type, at least locally.

Thus, as given here, the average well in limestone is considered to yield 300 gpm but in Lehigh County, Pennsylvania (10), it appears that it should be possible to develop wells that will yield 1,000 gpm.

In Westchester County, New York, a well in schist is reported to yield 400 gpm where 90 gpm or less would be expected in that formation. Here cost at the wellhead would be about 2 cents per thousand gallons instead of about $6\frac{1}{2}$ cents at the end of a well field consisting of multiple wells and connecting pipe.

Conversely, in some areas drilled wells may produce less than the average yields listed in table D-6 and in such instances costs would be higher than given here.

Therefore, site studies are a necessity to arrive at cost figures that take into account all relevant factors in any one specific locality. In this respect, it is clear that ground-water hydrologists should be called upon to advise on well locations in order that all geologic and hydrologic factors affecting the sustained yield of a well are taken into account and that costs are brought down to the minimum possible in the geologic-hydrologic environment being developed.

Although not applicable to site studies the order-of-magnitude costs given here should serve the broad planning purpose for which they are intended. It is pointed out that the generalized cost figures given were developed from a study of the North Atlantic Region and may not reflect physical or economic factors determining costs in other areas. However, the same methods of determining costs can be used in other areas.

It is not possible to state that a well in any one type of formation will yield exactly so many gallons a minute. Hence, it cannot be said that water from wells in any formation will cost so much per thousand gallons. Rather, the approach has necessarily been taken that if a well in glacial or in any formation yields 100 gpm and if the capital costs, the amortization rate and maintenance costs are much as stated, then the cost per thousand gallons will be about as given in the tables and shown on the graphs. With increasing number of wells in the system, the costs rise sharply at first, owing to the cost of connecting the wells by pipe and delivering the water to one end of the well field. Thus, the data presented here may be of greatest value after a preliminary assessment of a proposed site has been made. A skilled hydrologist can give an estimate of probable average yield of multiple wells in the area selected and, with that estimate in hand, the developer can arrive at a probable capital cost and cost per thousand gallons of water at one end of a well field. Broad ranges of obtainable yields in coastal plain and glacial sediments are given in the text. These data simply cannot be used to arrive at an idea of final costs without some knowledge of site conditions. Wells in those formations may yield almost no water if improperly located, but on the other hand may yield 2 million gallons a day or more per well if drilled in favorable parts of the aquifer.

The interest rate of 5-1/8 percent has been used for calculations of amortization costs of both ground- and surface-water structures in the North Atlantic Region Water Resources Study and has been considered realistic insofar as municipal and industrial developments are concerned from a long term point of view. A power cost of 1¢ per kilowatt hour, 200 feet lift of water, and prices as given are also basic assumptions inherent in the final costs per thousand gallons given in the charts and tables.

CHAPTER II

METHOD OF CALCULATING COSTS

PRICE LEVELS

The capital cost figures given in the tables reflect generalized costs as of early 1968. These were later revised to approximate 1970 costs. With prices sharply escalating at present due to inflation, users of these data will necessarily determine the price structure in their local market as of the year applicable, be it 1971 or some later year.

CONSTRUCTION AND EQUIPMENT COSTS

Drilling. It is necessary to make several assumptions upon which to base estimated costs. These assumptions are described in the following paragraphs.

In consolidated rock, down-the-hole hammer (air-rotary) equipment is assumed. Two 5-inch diameter holes are drilled to a depth of 400 feet, one of which is considered successful in producing the desired amount of water. The successful well is reamed to a depth of 125 feet and to a nominal diameter of 8 inches in order to accommodate the pump.

In glacial sediments, it is also assumed that two holes are necessary to obtain one successful well. It is assumed that the casing in the unsuccessful well will be recovered and the cost of drilling of that well will be less than that of the successful well. Figures are given for completion of wells at 75 feet and 200 feet depths inasmuch as there are considerable differences in depths of wells in glacial deposits but relatively few industrial or municipal wells are less or greater than the depths mentioned. Casing of sufficient diameter to accommodate the pump is given for the full length of the hole except for the 1,400 gpm wells where 24-inch casing is reduced to 18 inches at 40 feet. It is assumed that high yield wells in glacial sediments are recharged by a nearby large stream and the pumping setting will be generally within 40 feet of the surface although this relationship is by no means invariable.

In Coastal Plain sediments it is assumed that most of the wells are deep artesian wells and that they are located somewhat east of the Fall Zone where productive water-bearing sands are known to be generally present. Here a pilot hole is driven by conventional rotary machine to 500, 600, or 700 feet (table D-12A) and the well finished at those depths (or lesser depths in some instances). In every instance the upper 125 feet of the hole is finished with larger diameter casing than the lower portion in order to accommodate the pump. Provision is made for one unsuccessful well for each production well where the yield is 150 gpm. It is assumed that these will be wells along the Fall Zone where aquifers are more erratically distributed.

Casing diameters selected for the upper portion of the hole are those recommended for the setting of pumps (30) whereas the lower length of casing is of sufficient diameter to accept the optimum size screen. In some instances depending on the type of pump used, smaller diameter casing may be used in the upper part of the hole.

It is not inferred that the type of equipment mentioned is the optimum for drilling any particular type of earth material. Cable-tool rigs, for instance, have been and are presently used in hard rock and in glacial and Coastal Plain sediments with success and the jetting method is commonly used today in the Coastal Plain for smaller diameter wells.

Drilling costs generally prevailing in 1968 were raised by 10 percent to bring those costs to the 1970 level (tables D-12A, D-13A, and D-14A). Variations from place to place are likely, but even where costs are somewhat different from those shown, the net result, that is, the cost per thousand gallons, will not be greatly different from that given in the tables. For instance, in table D-13B, the cost of water from a 300 gpm well in consolidated rock is shown to be $.0219 per thousand gallons at the wellhead. If the capital cost of the well was $2,000 greater than the $14,926 shown, the cost per thousand gallons would work out as $.0239 instead of the $.0219 given in the table, a difference only of 2 mills per thousand gallons. Therefore, orders of magnitude arrived at for cost per thousand gallons will be generally applicable even though expected variations from the basic cost figures do occur.

Development. No allowance is made for development of wells drilled in consolidated rocks in that development will ordinarily occur as the holes are drilled and formational water is discharged. Development of rock wells, (wire brush scrubbing and raw hiding) is desirable in low yield rock wells, but may not be necessary in higher yield wells where water enters the well through larger openings.

Development costs are given for wells in glacial and Coastal Plain deposits. The higher yield wells are considered to require as much as four days work. Although some wells finished in granular sediments seemingly develop quickly, it is likely that the development indicated is desirable to insure maximum production and stability of the well.

Pump. The pump selected, in every instance, is a submersible pump set at 125 feet that will deliver quantities stated against a 200-foot head. Included with the pump are riser, cable, magnetic starter, check valve, and gate valve. Cost of installation is also included.

Obviously a 125-foot pump column could not be installed in some of the wells with dimensions given (table D-14A), but the cost difference between the dimension selected and a shorter column is small and this difference was ignored.

Screens. Screen installed in wells in glacial deposits and Coastal Plain sediments are designed to permit entrance of the volumes states at a recommended entrance velocity of 0.1 ft per second (30). Costs of screen include fittings and $110 for setting the screen.

Pump Test. A capacity test is provided for in every instance for completed wells, ranging up to four days in duration for the highest yield wells. In some few instances the test run allowed for may be made by the municipality or by the industry staff after installing the permanent pump.

No provision is made for observation wells for aquifer testing to determine optimum spacing of wells, entrance losses, or other factors.

House and Lot. The cost of a lot is assumed to be $1,000 (plus 10%) although it is likely that in many instances the well may be located on public property or on company property and the cost of a lot will not be applicable.

The well house is considered to cost $1,500 (plus 10%). In some instances this cost may be much less.

Connecting Pipe. Pipe costs are calculated from data given in a chart (fig. D-14) shown in Office of Saline Water Research and Development Report No. 257 (U.S. Dept. of the Interior, 1966) (31). The chart is based on data submitted by the firm of Lockwood, Andrews and Newman to the Texas Water Development Board in 1965 and a report by the firm of Black and Veatch submitted to the Office of Saline Water 1963. To bring costs to the 1970 level, costs given in the publication referred to were increased by one-third, as shown in fig. D-14.

In the various well field plans shown in the tables, the cost of connecting pipe is selected for pipe large enough to carry the full capacity of all the wells in either direction along the trunkline. If the pipe were graduated in size from one end of a well field to the other, costs of the trunkline would be about 55 percent of those shown.

Where a well field consists of a trunkline and laterals, as in figure D-16, laterals are only large enough to deliver the output of one well to the trunkline.

The series of calculations for costs of connecting pipe are applicable where a new well field is to be established and a complete system is to be built. Obviously many additions to existing systems will be constructed in the future and in such instances advantage will be taken of pipe already in the ground. Costs of, say, 3 or 4 new wells may work out as little more than multiples of single well costs rather than the cost of a 3- or 4- well system with connecting pipe shown in the tables.

As brought out in more detail in the discussion of each of the three types of aquifers considered, well spacing, and therefore pipe costs, is based on certain conservative assumptions of recharge.

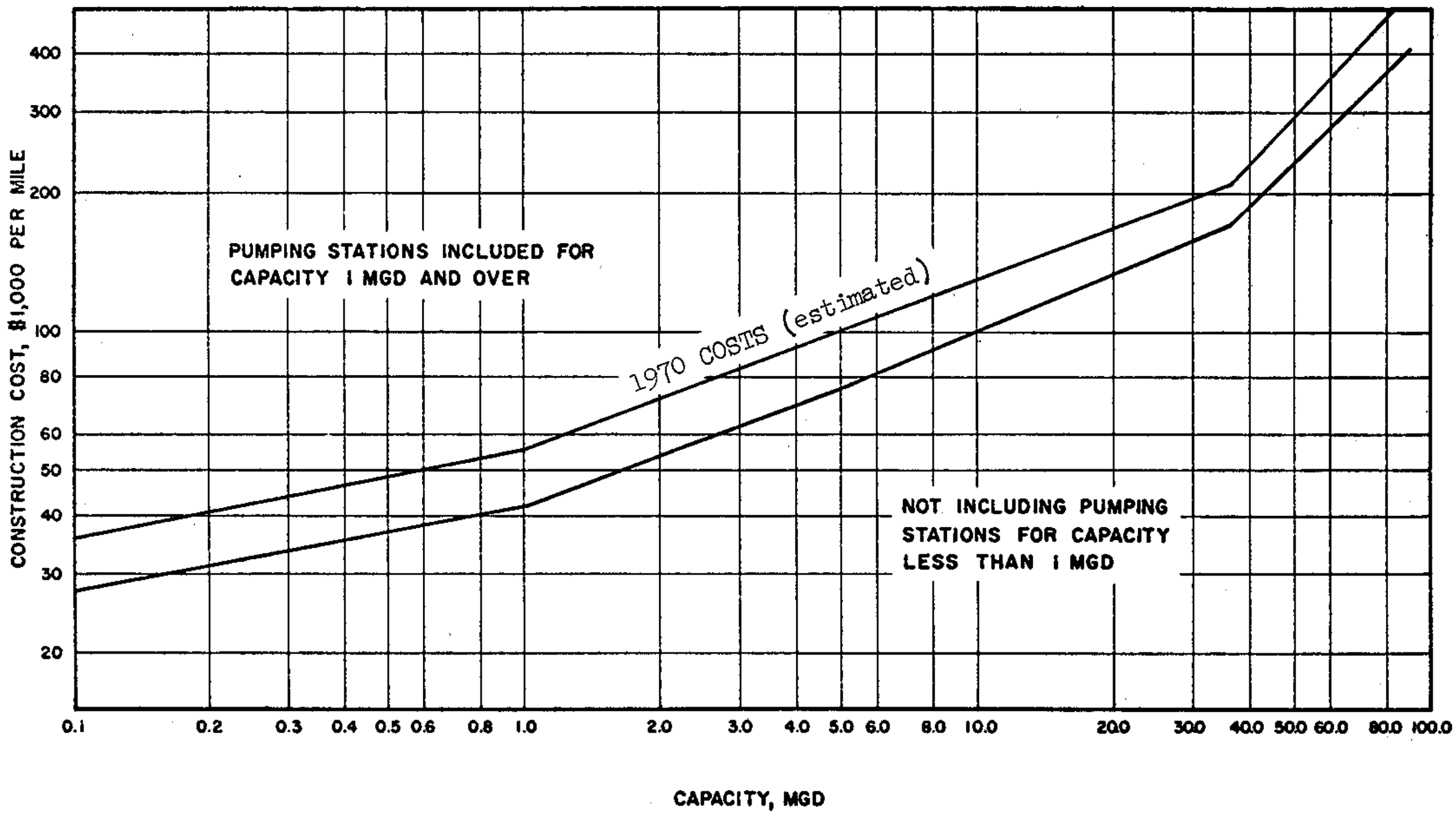


Figure D-14.--Pipeline construction costs. Total construction cost versus throughput capacity (including pumping stations for above 1 mgd).

It may be found in many places that little or much more recharge is available than assumed here. Where this is true, wells may be more closely spaced and pipe costs will be less than given here.

In other situations where, say, 10 wells are to be constructed, 2 separate well fields might be developed. Costs would then be calculated as those applicable to a 6-well and a 4-well field, perhaps, rather than to a 10-well field.

Transmission line from the well head or from one end of the well field to the point of use or to a system of mains is a cost item that must be considered separately. Cost of transmission from the well field is not included here because of the great variations in that item. The transmission line might be a matter of a few hundred feet or it might be several miles in length, depending on the site situation. In comparing costs of a ground-water supply with that of an alternative surface water supply, transmission costs must be determined for water from either source in order to arrive at a realistic cost appraisal.

Easements. Cost of right-of-way is considered to be $500 per mile.

Power. Power is assumed to be available at 1¢ per kilowatt hour. At 200-foot head, the cost of pumping is $.009 per thousand gallons (32, 33). It is again clear that in the assumptions made in this report, pumping head will be generally less. However, the delivery of water to a storage facility will ordinarily require applied pressure in addition to that necessary to lift water in the well to the surface of the ground. Hence, the power cost used may represent a good generalized figure.

Engineering Costs. An "engineering" cost of 15 percent is applied to the capital costs of wells. This percentage is intended to cover an appraisal by a hydrologist and such professional inspection of the drilling and development operations and the test run, as may be needed.

The data pertaining to pipeline costs used here include a 25 percent assessment for engineering and contingency. Hence, in the tables given later, engineering and contingency costs are shown as separate items only in the costs of wells.

Contingency. Ten percent is allowed for contingencies. This 10 percent plus 15 percent engineering cost is applied to capital costs of well construction in order to arrive at Total Capital Costs of wells shown in the tables. With respect to connecting pipe in multiple well developments as derived from the chart (fig. D-14), a 25 percent engineering and contingency cost is included in the costs shown and hence, is not given as such in tables D-12C, D-13C and D-14C, D.

AMORTIZATION

The Grant and Ireson capital-recovery equation (34) was used to determine annual payments necessary to cover interest on the initial cost of well installations and payments to a depreciation fund over a 25-year period. On the basis of money borrowed at 5-1/8 percent annual interest, the factor is .0718. Annual payments then simply become capital costs multiplied by that factor.

MAINTENANCE

It was estimated that 1 percent per annum of total capital costs would be ample to provide for maintenance of the wells. Maintenance of pipeline is taken as the standard .25 percent per annum of capital cost of the pipeline.

MAXIMUM SYSTEM CAPACITY AND DAILY DISCHARGE

In cost tables set up in this discussion the maximum yield of individual wells and the capacity of a system of multiple wells is based on discharge as determined from relatively short-term pumping tests. However, a lesser "daily discharge" is listed that is only 60 percent of the "maximum system capacity."

Assuming that a well has a yield of, say, 300 gpm as determined from a short-term pumping test, that yield may decline somewhat in periods of protracted dry weather during which there is negligible local recharge and water levels decline. It is believed that assigning a sustained yield ("daily discharge") of 180 gpm to such a well is more than sufficient to compensate for the lower yields that might be obtained during these infrequent periods of diminished recharge and greater reliance upon ground storage. In any event, it is thought to be good engineering practice that the pumps not operate on an essentially continuous basis. As set up in the tables, the pumps run 60 percent of the time to supply an average of 180 gpm from a well rated at 300 gpm. In times of drought, the pumps will necessarily run longer each day in order to supply the same average of 180 gpm because with lower water levels the rated capacity would be expected to decline somewhat.

CALCULATION OF COSTS PER THOUSAND GALLONS

The cost of water per thousand gallons at the wellhead is calculated, first (1) by multiplying the capital costs by the amortization factor to find the annual amortization charge, (2) adding the annual maintenance charge to obtain the total annual cost, (3) dividing the total annual cost by 365 to find the daily cost, and (4) dividing that cost by the number of thousands of gallons of water pumped per day. This then gives the cost per thousand gallons for amortizing the capital costs of completing the well, maintaining the equipment, and replacing the equipment as needed. To this is added the cost of pumping the water, $.009 per thousand gallons.

Where multiple-well discharge is considered, the cost of connecting pipe is determined for various combinations (fig. D-16) and that cost amortized and charged off on the basis of water delivered, as is done with the well installations. The cost per thousand gallons for pipe is then added to the cost of the water at the wellhead.

<u>The cost per thousand gallons at the wellhead from a single well and the cost at the wellhead from three wells, each of which produces as much as the first well, is the same</u>. Capital costs are three times as great, but the daily discharge is also three times as great and, therefore the cost per thousand gallons is the same. As the number of wells in a unit increases, the only added cost <u>per thousand gallons</u> is the cost of the connecting pipe. Were it not for the added cost of connecting pipe in multiple well fields, the lower curve (cost per thousand gallons) in the graphs (figs. D-15, D-17, and D-18) would be horizontal regardless of the number of wells in the system, although the capital costs curve would slant upward as the number of wells in the system was increased.

Moderate adjustments of capital costs as given here will make no significant difference in the calculation of the cost of water to the consumer. Increasing the capital costs of pipe, or any other item, represents the investment of that much more money but when the increased expenditure is amortized over a period of 25 years and scaled to the cost per thousand gallons, the consumer who is paying for the water on his monthly water bill, will find the increased cost negligible. This topic is dealt with in more detail below.

There is no economy of scale in the usual sense. Additional wells in a system cost about as much as the initial wells and, further, pipeline costs increase per unit of water even if the pipeline is graduated throughout.

CHAPTER III

THE COASTAL PLAIN AQUIFERS

AVAILABLE SUPPLIES

The Coastal Plain formations consist of a series of sand, gravel, and clay beds that dip gently seaward. They are thin along the Fall Zone, but thicken to 5,000 feet or more along the Atlantic Coast.

The surficial sands are thick and somewhat coarse in Long Island, New Jersey, Delaware, and eastern Maryland. Water in rather large quantity can be obtained from them by wells generally less than 500 feet deep. Yields of individual wells may be high, as much as 2,000 gpm (gallons per minute) where the greater thicknesses of coarse material is present. In western Maryland and Virginia the surficial sands are thin and yields of individual wells are low.

The deep artesian beds of the Coastal Plain are among the best aquifers in the North Atlantic Region. Wells range up to 1,000 feet in depth and yields of over 2 mgd (million gallons a day) may be available in many places, generally ten or more miles east of the Fall Zone. (The initial yield of an artesian well at Franklin, Va., was $4\frac{1}{2}$ mgd.) At varying distances seaward the deep artesian beds contain brackish water. Large quantities of water should not be developed close to the fresh water - brackish water boundary in most circumstances. As brought out in a preceding section of this paper, development of Coastal Plain water is limited by the volume of recharge, presently a very general estimate. Developments of very large quantities will best proceed by stages, with aquifer response carefully noted and interpreted at each stage.

Near the Fall Zone, the area where the Coastal Plain sediments lap up against the inland consolidated rocks, only small supplies are available. In most instances, wells there will not yield more than a few hundred gallons a minute.

COST OF WATER

The following tables (D-12A-D) show estimates of costs for wells ranging in yield from 150 gpm (a little less than $\frac{1}{4}$ mgd) to 1,400 gpm (2 mgd) and where well fields consist of wells arranged linearly and 1,000 feet apart. These data are also plotted and show as fig. D-15. Other well field designs may be as economic

TABLE D-12A.--WELLS IN COASTAL PLAIN SEDIMENTS--CAPITAL COSTS OF WELLS.

Yield (gpm)	Production well[a]	Screen	Develop	Pump	Test run	House and lot	Sub-total	Eng. & cont.	Total capital cost 1968	Total capital cost 1970
150	$5,100 300' x 6"	$350 5' x 6"	$400 2 days	$2,100	$480 24 hrs	$2,500	$10,930	$2,732	$13,662	$15,028
350	$7,500 375' x 8" 125' x 10"	$875 13' x 8"	$400 2 days	$3,400	$480 24 hrs	$2,500	$15,155	$3,788	$18,943	$20,837
700	$12,800 475' x 10" 125' x 14"	$1,495 21' x 10"	$600 3 days	$5,040	$960 48 hrs	$2,500	$23,395	$5,849	$29,244	$32,168
1,400	$25,100 575' x 12" 125' x 20"	$2,795 42' x 10"	$1,200 4 days	$8,800	$960 48 hrs	$2,500	$41,255	$10,264	$51,519	$56,670

a/ One unsuccessful well for each production well at 150 gpm only.

TABLE D-12B.--WELLS IN COASTAL PLAIN DEPOSITS--AMORTIZATION AND OPERATIONAL COSTS AND UNIT COST OF WATER.

Yield (gpm)	[a] Capital costs	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal. Equip. & maint.	Cost per 1,000 gal. Power	Cost per 1,000 gal. Total
150	$15,028	$1,082	$150	$1,232	$3.37	130	$.0259	$.009	$.035
350	$20,837	$1,503	$208	$1,711	$4.68	300	$.0156	$.009	$.025
700	$32,168	$2,316	$322	$2,638	$7.23	600	$.0123	$.009	$.021
1,400	$56,670	$4,082	$567	$4,649	$12.74	1,200	$.0106	$.009	$.020

TABLE D-12C.--WELLS IN COASTAL PLAIN DEPOSITS--COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS.

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
				Wells yield 150 gpm							
1	.216	--	--	--	--	--	--	--	--	--	$.035
2	.432	$ 4,470	$ 47	$ 4,517	$ 325.2	$ 11.8	$ 336	$ .92	260	$.0035	.038
5	1.08	21,660	189	21,849	1,573	54.2	1,627	4.45	650	.0069	.042
10	2.16	63,490	426	63,916	4,602	159	4,761	13.04	1,300	.0101	.045
20	4.32	172,235	899	173,134	12,466	431	12,897	35.33	2,600	.0136	.049
50	10.8	635,646	2,318	637,964	45,933	1,589	47,522	130.19	6,500	.0200	.055
100	21.6	1,683,750	4,683	1,688,433	121,567	2,959	124,526	341.16	13,000	.0263	.061
				Wells yield 350 gpm							
1	0.5	--	--	--	--	--	--	--	300	--	.0246
2	1.0	9,323	95	9,418	678	23	701	1.92	600	.003	.028
3	1.5	20,615	189	20,804	1,498	52	1,550	4.24	900	.005	.029
4	2.0	33,995	284	34,279	2,468	85	2,553	6.99	1,200	.005	.030
5	2.5	54,424	378	54,802	3,946	136	4,082	11.18	1,500	.008	.032
10	5.0	165,451	851	166,302	11,974	414	12,388	33.93	3,000	.011	.036
20	10.0	473,813	1,797	475,610	34,244	1,185	35,429	97.06	6,000	.016	.041
40	20.0	1,276,824	3,689	1,280,513	92,197	3,192	95,389	261.30	12,000	.022	.046
65	32.5	2,578,870	6,000	2,584,870	186,111	6,447	192,558	527.55	19,500	.027	.052
80	40.0	3,879,610	7,481	3,887,091	279,871	9,699	289,570	793.34	24,000	.033	.058

TABLE D-12C.--WELLS IN COASTAL PLAIN DEPOSITS--COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS--continued.

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
				Wells yield 700 gpm							
1	1	--	--	--	--	--	--	--	600	--	$.0213
2	2	$ 10,307	$ 95	$ 10,402	$ 749	$ 26	$ 775	$ 2.12	1,200	$.0018	.023
3	3	27,212	189	27,401	1,973	68	2,041	5.59	1,800	.0031	.024
4	4	47,600	284	47,884	3,447	119	3,566	9.76	2,400	.0041	.025
5	5	70,530	473	71,003	5,112	176	5,288	14.49	3,000	.0048	.026
10	10	215,460	851	216,311	15,574	539	16,113	44.14	6,000	.0074	.029
20	20	621,110	1,797	622,907	44,849	1,553	46,402	127.13	12,000	.0106	.032
33	33	1,289,568	3,027	1,292,595	93,067	3,224	96,291	267	19,800	.014	.035
40	40	1,932,091	3,689	1,935,780	211,376	4,830	216,206	592	24,000	.025	.046
				Wells yield 1,400 gpm							
1	2	--	--	--	--	--	--	--	1,200	--	.0196
2	4	13,606	95	13,701	986	34	1,020	2.79	2,400	.00116	.0207
3	6	35,272	189	35,461	2,553	88	2,641	7.23	3,600	.00201	.0216
4	8	61,965	284	62,249	4,482	155	4,637	12.70	4,800	.00264	.0222
5	10	91,664	473	92,137	6,634	229	6,863	18.80	6,000	.00313	.0227
10	20	283,210	851	284,061	20,452	708	21,250	58.21	12,000	.00485	.024
16	32	585,200	1,419	586,619	42,236	1,463	43,699	119.72	19,200	.00624	.026
20	40	885,461	1,797	887,258	63,883	2,214	66,097	181.09	24,000	.00755	.027
25	50	1,389,850	2,270	1,392,120	100,233	3,475	103,708	284.13	30,000	.00947	.029

12-D.--SUMMARY OF CAPITAL COSTS OF MULTIPLE WELL SYSTEMS IN COASTAL PLAIN SEDIMENTS.

No. of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells	Cost of pipeline	Total capital cost
		Wells yielding 150 gpm			
1	0.216	0.13	15,028	- -	15,028
2	0.432	0.26	30,056	4,517	34,573
5	1.08	0.65	75,140	21,849	96,989
10	2.16	1.3	150,280	63,916	214,196
20	4.32	2.6	300,560	173,134	473,694
50	10.8	6.5	751,400	637,964	1,389,364
100	21.6	13.0	1,502,800	1,688,433	3,191,233
		Wells yielding 350 gpm			
1	0.5	0.3	20,837	- -	20,837
2	1.0	0.6	41,674	9,418	51,092
3	1.5	0.9	62,511	20,804	83,315
4	2.0	1.2	83,348	34,279	117,627
5	2.5	1.5	104,185	54,802	158,987
10	5.0	3.0	208,370	166,302	374,672
20	10.0	6.0	416,740	475,610	892,350
40	20.0	12.0	833,480	1,280,513	2,113,993
65	32.5	19.5	1,354,405	2,584,870	3,939,275
80	40.0	24.0	1,666,960	3,887,091	5,554,405
		Wells yielding 700 gpm			
1	1	0.6	32,168	- -	32,168
2	2	1.2	64,336	10,402	74,738
3	3	1.8	96,504	27,401	123,905
4	4	2.4	128,672	47,884	176,556
5	5	3.0	160,840	71,003	231,843
10	10	6.0	321,680	216,311	537,991
20	20	12.0	643,360	622,907	1,266,267
33	33	19.8	1,061,544	1,292,595	2,354,139
40	40	24.0	1,286,720	1,935,780	3,222,500
		Wells yielding 1,400 gpm			
1	2	1.2	56,670	- -	56,670
2	4	2.4	113,340	13,701	127,041
3	6	3.6	180,010	35,461	215,471
4	8	4.8	226,680	62,249	288,929
5	10	6.0	283,354	92,137	375,491
10	20	12.0	566,700	284,061	850,761
16	32	19.2	906,720	586,619	1,493,339
20	40	24.0	1,113,340	887,258	2,000,598
25	50	30.0	1,416,750	1,392,120	2,808,870

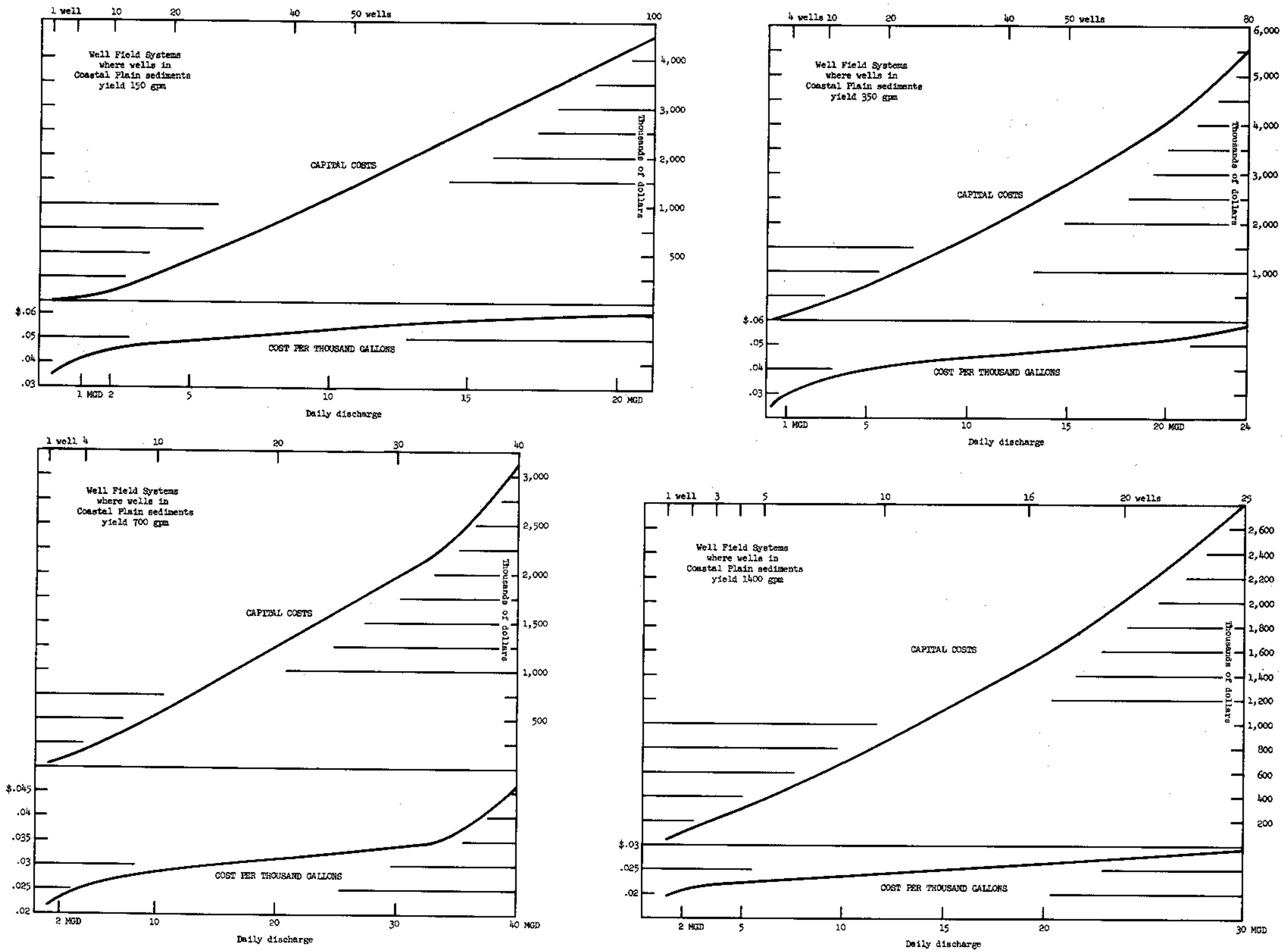


Figure D-15.--Graphs showing capital costs and cost per thousand gallons of water from wells in Coastal Plain sediments.

or even more so, depending on many factors to be determined after site studies have been made. The data can be used only as a general guide to approximate costs if wells of stated yields can be developed and are constructed according to the pattern used and cost assumptions made. In most instances, site studies will show approximately what yields will be obtained in an area, but other factors influencing actual costs will have to be determined by the developer and applied against the estimates given here.

CHAPTER IV

THE CONSOLIDATED ROCKS

YIELDS OF WELLS

The yield of a well in consolidated rock may be almost nothing or many hundreds of gallons a minute. Further, it can be shown that the "average yield" of wells in any one area, as commonly given in the literature, is no guide to what might be obtained, because most existing wells were constructed to supply water for domestic use. The "average yield" as determined from a consideration of all well yields in an area, therefore, represents something a little greater than the average <u>need</u> and is not a measure of the full potential of wells in the rock type being studied.

A detailed study was made of published records of municipal and industrial wells in the North Atlantic Region as a basis for determining the average yields used here, on the assumption that when these wells were drilled, an effort was made to obtain a maximum supply of water. About 1,500 of about 15,000 published well records were selected and used as the basis for arriving at the yield figures in this report. Most of these wells were drilled to a depth of 350 feet or more and utilized about 100 feet of drawdown. The manipulations of the data and other aspects of that study will not be dealt with here. The assumptions are that the depth and drawdown assumptions are as stated, the average yields are as given in the table and refer to wells that are somewhat widely distributed (e.g., 3 "dry" wells drilled within a few tens of feet of each other near a water tank are considered as one well). It is also assumed that well locations are selected by a hydrologist.

The number of wells to be drilled before the "sample" is large enough to yield the average is problematical. Perhaps five should be sufficient where the first one or two wells do not approach the average given in table 2. With this real possibility in mind, producing well costs given in tables D-13A-D include the cost of one unsuccessful test hole. Thus, where three wells of average yield are sought, costs include the drilling of a total of six holes.

THE CRYSTALLINE ROCKS

Crystalline rocks, largely granites, schists and gneisses, underlie most of the Piedmont Province, the Blue Ridge, the New England Upland, and the Adirondacks. Yields from wells in these rocks are generally low. Where the rocks are greatly fractured, as along prominent faults, a few hundred gallons per minute per well may be obtained, but ordinarily the average yield of properly located wells 350 to 450 feet deep in these rocks is 75 to 100 gpm (gallons per minute). Wells located in valleys, generally areas of more highly-developed fractures, will ordinarily have the better yields, as will wells in areas overlain by thick saturated weathered rock or glacial sands. Prominent ridges commonly are underlain by solid rock masses and are poor locations for wells. Yields of wells there may be only a few gallons a minute and the cost of water very high.

Marble is associated with other crystalline rocks in a few places. Wells in marble may have higher yields than those in the other crystalline rocks.

THE CONSOLIDATED SEDIMENTARY ROCKS

Consolidated sedimentary rocks, limestone and dolomite (carbonate rocks), sandstone, and shale make up the Valley and Ridge and Appalachian Plateau Provinces.

The carbonate rocks are commonly excellent water-bearing formations. The average yield of wells in multiple well developments in the older massive limestones is about 300 gpm. However, some wells in limestone yield very little water and others are known to yield more than 1,000 gpm.

Deep well yields in sandstones of the Appalachian Valley generally average about 150 gpm in multiple well developments. Sandstone and associated rocks of Triassic age are present in central Connecticut and as a belt of variable width extendi-- from southeastern New York into Virginia. These rocks lie with .. the larger crystalline rock areas. They are made up of alternating sandstones and shales with some interbedded volcanics. Deep wells in the sandstones and associated conglomeratic rocks have an average yield of about 150 gpm. The shales and volcanic rocks yield much less water.

Shale is a poor water-bearing formation. Wells in true shale, such as is present in the Plateau Province, probably have average yields of not more than about 40 gpm but in the Valley and Ridge Province, wells in the slaty or sandy shales may average about 75 gpm. Significant increments of water are generally not obtained below 250 feet in true shales but wells in sandy or slaty shales generally gain in yield down to a depth of about 400 feet or more.

The figures given in table D-6 do not guarantee the yields that will be obtained. They reflect what has been found to be true in many places and what is a reasonable probability elsewhere. Where there are marked departures from general geologic conditions, yields may be notably different from those given. Deep wells in the crystalline rocks of the Blue Ridge will undoubtedly have much poorer yields than wells in similar rocks in the Piedmont where the rocks are overlain by a thick blanket of saturated weathered material. In one area where sandstones are overlain by stratified glacial sands, the average yield of 117 municipal and industrial wells is 300 gpm rather than the 150 gpm shown in the table. Other variations from the averages given will undoubtedly be found in test drilling new localities.

In applying the cost estimates given below, therefore, it is necessary to determine the rock type in order to have some idea of yields expected, and, in turn, the order of magnitude of costs.

RECHARGE

It is quite clear that many productive wells may be developed in the consolidated rocks of the North Atlantic Region. However, when the task of evaluating the cost of water in large quantity is undertaken, determination of the probable yield of multiple wells is only part of the answer to the problem. The other part of the problem is to determine how much water a unit area of ground will furnish under continuous pumping conditions.

For broad planning purposes, it is assumed that recoverable recharge averages $\frac{1}{2}$ mgd per square mile in areas underlain by limestone and sandstone south of the glaciated area. It may be somewhat less where those rocks are overlain by glacial till. The recharge rate in the crystalline rock areas were also calculated on the basis of $\frac{1}{2}$ mgd per square mile although recharge may exceed that figure slightly where those rocks are overlain by a thick weathered mantle and may be much less in northern areas of rugged topography where the rocks are overlain by glacial till. Shaly areas are considered to be recharged at an average rate of $\frac{1}{4}$ mgd per square mile.

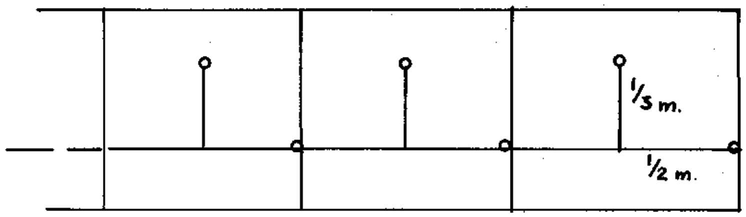
In the cost analyses given below the recharge per square mile is taken into account with respect to spacing of wells and cost of pipeline in crystalline rocks, sandstones, limestones and shales (fig. D-14). For example, in this report it is considered that in a limestone terrain, five wells will produce about 1-3/4 mgd from a catchment area of $2\frac{1}{2}$ square miles. At Elkton, Virginia, a plant manager stated that five wells there spaced 15 feet apart yield $8\frac{1}{2}$ mgd. Such very favorable situations are necessarily disregarded in the cost analyses given here.

As noted above it is also assumed that no significant infiltration from streams, from capture of extra runoff, from reduction of evapotranspiration occurs and that there is no reuse (recycling) of water pumped. These factors will be operative in many instances, and more water will be available and at less cost, particularly less pipeline cost, than is assumed in the calculations but the determination of possible gains is difficult except in detailed site studies.

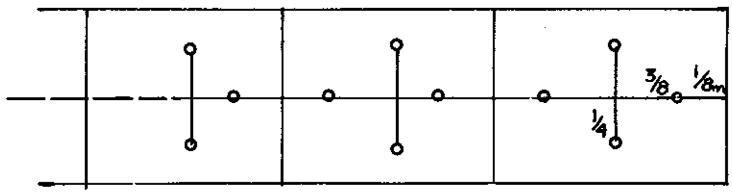
Further, theoretical well fields are laid out linearly and possible gains from water drifting in from outside each square mile are also not considered in the calculations. Thus, if a well field one mile wide extends five miles, according to the approach taken here, additional ground water could be obtained from another immediately adjacent well field five miles long and one mile wide, without violating basic hydrologic principles on these calculations.

COST OF WATER

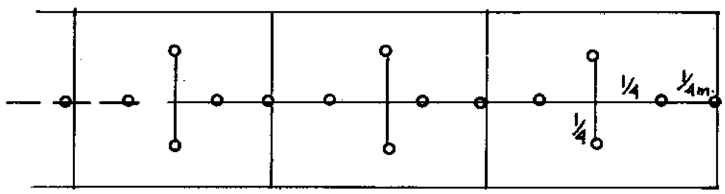
Tables D-13A-E below show the estimated cost of water where well yields in consolidated rocks range from 75 to 300 gpm and where wells are spaced according to the patterns shown in figure D-16. As inferred, other arrangements are possible and may be preferable after conditions at any potential site are determined.



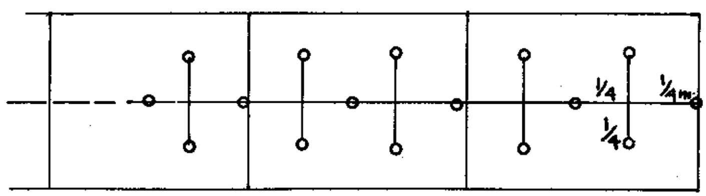
Wells yield 300 gpm



Wells yield 150 gpm



Wells yield 100 gpm



Wells yield 75 gpm

Figure D-16.--Sketch showing arrangement of wells in consolidated rocks where average annual recharge is about $\frac{1}{2}$ million gallons a day per square mile.

TABLE D-13A.--WELLS IN CONSOLIDATED ROCKS--CAPITAL COSTS OF WELLS.

Yield (gpm)	Test well	Production well	Total drilling	Pump	Test run	House and lot	Sub-total	Eng. & cont.	Total capital cost 1968	1970
75	($2,000) (400' x 5")	($2,375) (125' x 8") (275' x 5")	$4,375	$1,430 75 gpm	$360 24 hrs	$2,500	$8,665	$2,166	$10,831	$11,914
100	($2,000) (400' x 5")	($2,375) (125' x 8") (275' x 5")	$4,375	$1,700 100 gpm	$360 24 hrs	$2,500	$8,935	$2,233	$11,168	$12,285
150	($2,000) (400' x 5")	($2,375) (125' x 8") (275' x 5")	$4,375	$2,100 150 gpm	$360 24 hrs	$2,500	$9,335	$2,334	$11,669	$12,836
300	($2,000) (400' x 5")	($2,375) (125' x 8") (275' x 5")	$4,375	$3,500 300 gpm	$480 24 hrs	$2,500	$10,855	$2,714	$13,569	$14,926

TABLE D-13B.--WELLS IN CONSOLIDATED ROCKS--AMORTIZATION AND OPERATIONAL COSTS AND UNIT COST OF WATER.

Maximum yield (gpm)	Depth (feet)	Capital costs	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal. Equip. & maint.	Power	Total
75	400	$11,914	$ 858	$120	978	$2.67	64	$.0418	$.009	$.0498
100	400	12,285	885	123	1,008	2.75	87	.0316	.009	.0406
150	400	12,836	924	128	1,052	2.89	130	.0290	.009	.0303
300	400	14,926	1,075	150	1,225	3.37	260	.0129	.009	.0219

TABLE D-13C.--WELLS IN CONSOLIDATED ROCKS--COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS.

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
					Wells yield 75 gpm						
1	.108	--	--	--	--	--	--	--	64	--	$.0498
4	.43	$ 39,900	$ 500	$ 40,400	$ 2,909	$ 99.75	$ 3,009	$ 8.24	256	$.032	.082
6	.65	73,815	875	74,690	5,378	184.53	5,563	15.24	388	.039	.089
12	1.28	187,530	1,875	189,405	13,637	468.83	14,106	38.65	780	.050	.100
24	2.59	435,575	3,875	439,450	31,568	1,088.94	32,657	89.47	1,560	.057	.107
48	5.18	1,074,906	7,875	1,082,781	77,960	2,687.00	80,647	220.95	3,110	.071	.120
72	7.78	1,837,790	11,875	1,848,165	133,067	4,595.00	137,662	377.16	4,670	.081	.131
					Wells yield 100 gpm						
1	0.144	--	--	--	--	--	--	--	86.4	--	.0406
5	.72	48,810	625	49,435	3,555	122	3,677	10.07	432	.023	.064
10	1.44	145,635	1,375	147,010	10,585	364	10,949	29.99	864	.035	.076
20	2.88	381,377	2,875	384,252	27,666	953	28,619	78.40	1,740	.045	.086
30	4.34	666,330	4,375	670,705	48,291	1,666	49,957	136.86	2,590	.053	.094
40	5.76	978,880	5,875	984,755	70,902	2,447	73,349	200.95	3,456	.058	.099
70	10.10	2,098,740	10,375	2,109,115	151,856	5,246	157,102	430.41	6,056	.071	.112

TABLE D-13C.--WELLS IN CONSOLIDATED ROCKS--COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS--continued.

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
					Wells yield 150 gpm						
1	.216	--	--	--	--	--	--	--	130	--	$.0303
2	.43	$ 17,689	$ 315	$ 18,004	$ 1,296	$ 44	$ 1,340	$ 3.67	260	$.014	.044
3	.64	38,570	435	39,005	2,808	96	2,904	7.95	390	.020	.050
4	.85	59,185	625	59,810	4,306	148	4,454	12.20	515	.024	.054
8	1.71	162,260	1,375	163,635	11,782	406	12,188	33.39	1,030	.032	.062
12	2.56	278,635	2,150	280,785	20,216	697	20,913	57.29	1,545	.037	.067
16	3.42	409,640	2,980	412,620	29,709	1,024	30,733	84.20	2,060	.041	.071
20	4.28	548,990	3,620	552,610	39,787	1,372	41,159	112.76	2,575	.044	.074
40	8.56	1,423,100	7,375	1,430,475	102,994	3,558	106,552	291.92	5,150	.056	.086
72	15.5	3,156,689	13,375	3,170,064	228,245	7,892	236,137	646.95	9,330	.069	.099
					Wells yield 300 gpm						
1	.43	--	--	--	--	--	--	--	257	--	.0219
2	.86	39,408	417	39,825	2,867	99	2,966	8.16	515	.016	.038
4	1.7	125,246	1,084	126,330	9,096	313	9,409	25.77	1,030	.025	.047
6	2.6	246,715	1,750	248,465	17,889	617	18,506	50.70	1,543	.033	.055
12	5.1	543,970	3,750	796,185	57,325	1,337	58,622	160.50	3,090	.052	.074
36	15.4	3,029,740	11,500	3,041,240	218,969	7,574	226,543	622.50	9,261	.068	.090
60	25.7	6,089,405	19,750	6,109,155	439,859	15,220	455,079	1,250.00	15,400	.079	.101
80	34.4	8,928,300	25,925	8,954,225	644,700	22,320	667,020	1,830.00	20,640	.086	.108
100	42.3	10,391,000	38,100	13,858,100	997,783	25,977	1,025,760	2,805.00	25,750	.109	.131

TABLE 13-D.---SUMMARY OF CAPITAL COSTS OF MULTIPLE WELL SYSTEMS IN CONSOLIDATED ROCKS.

No. of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells	Cost of Pipe line	Total capital costs
		Wells yielding 75 gpm			
1	0.11	0.64	$ 11,914	—	$ 11,914
4	0.43	0.26	47,656	$ 40,400	88,056
6	0.65	0.39	71,484	74,690	146,174
12	1.28	0.78	142,968	189,405	332,373
24	2.59	1.56	285,936	439,450	725,386
48	5.18	3.11	571,872	1,082,781	1,654,653
72	7.78	4.67	857,808	1,848,165	2,705,973
		Wells yielding 100 gpm			
1	0.144	.086	12,285	—	12,285
5	0.72	.43	61,425	49,435	110,860
10	1.44	.86	122,850	147,010	269,860
20	2.88	1.74	255,700	384,252	639,952
30	4.34	2.6	368,550	670,705	1,045,555
40	5.76	3.5	491,400	984,755	1,476,155
70	10.10	6.1	859,950	2,109,115	2,969,065
		Wells yielding 150 gpm			
1	0.216	0.130	12,836	—	12,836
2	0.43	0.26	25,672	18,004	43,676
3	0.64	0.39	38,508	39,005	77,513
4	0.86	0.52	51,344	59,810	111,154
8	1.7	1.03	102,688	163,635	266,323
12	2.6	1.6	154,032	280,785	434,817
16	3.4	2.1	205,376	412,620	617,996
20	4.3	2.6	256,720	552,610	809,330
40	8.6	5.2	513,440	1,430,475	1,943,915
72	15.5	9.3	1,026,880	3,170,064	4,196,944
		Wells yielding 300 gpm			
1	0.43	0.26	14,926	—	14,926
2	0.86	0.52	29,852	39,825	69,677
4	1.7	1.03	59,704	126,330	255,711
6	2.6	1.5	89,556	248,465	338,021
12	5.1	3.1	179,112	796,185	975,297
36	15.4	9.3	537,336	3,041,240	3,578,576
60	25.7	15.4	895,560	6,277,250	7,172,810
80	34.3	20.6	1,194,080	8,954,225	10,148,305
100	42.3	25.4	1,492,600	13,858,100	15,350,700

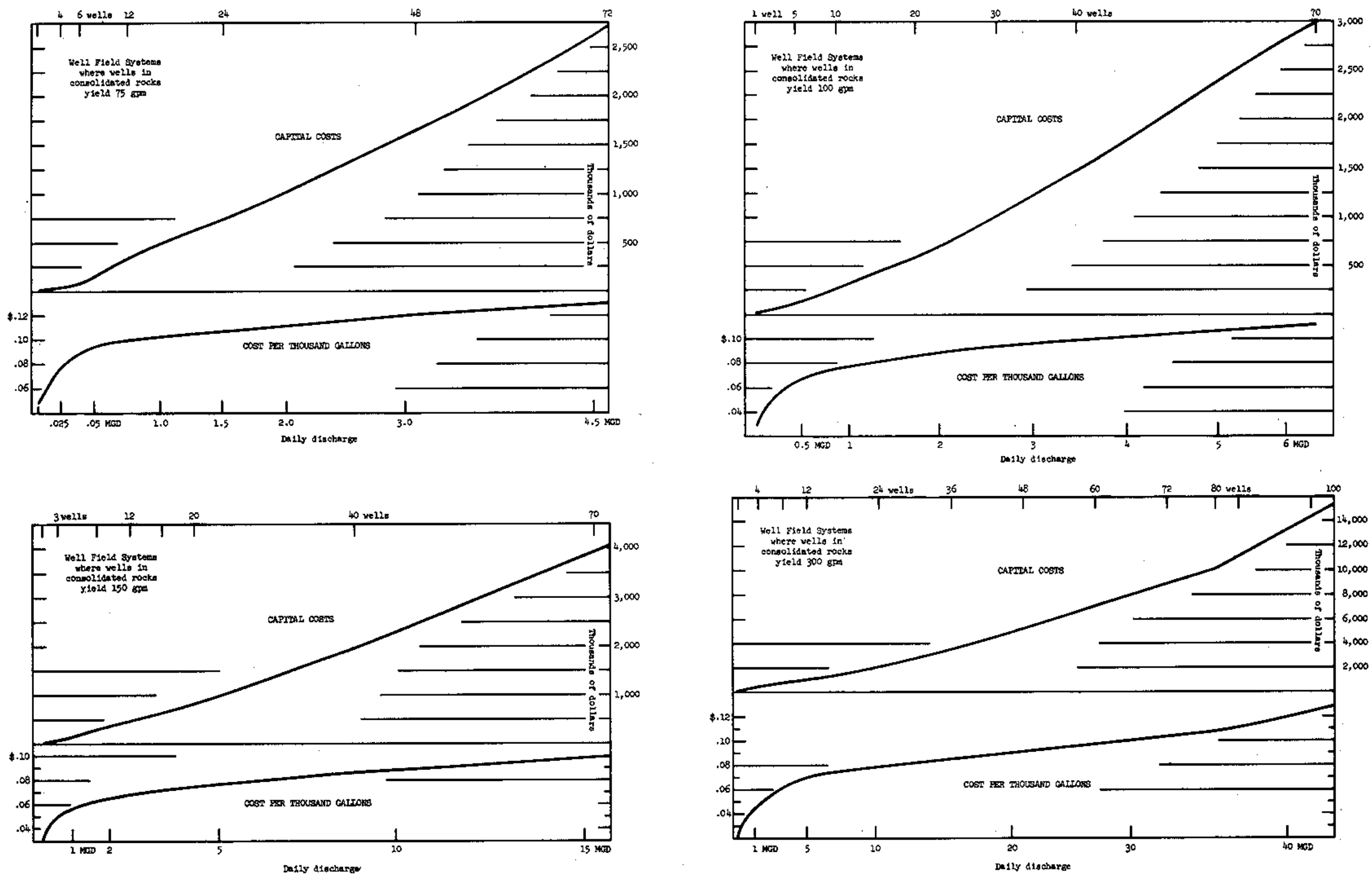


Figure D-17.--Graphs showing capital costs and cost per thousand gallons of water from wells in consolidated rocks.

CHAPTER V

GLACIAL DEPOSITS

DISTRIBUTION

Glacial aquifers considered here are the stratified sands and gravels that are most widely distributed as valley fill adjacent to streams and rivers. Till, an ill-sorted mass of ground up rock and fragmental material, is not considered an aquifer insofar as this report is concerned. The occurrence of the sand and gravel deposits is highly irregular and the prediction of quantities of water available and hence, the cost of producing water at any one locality can only be arrived at after determination of conditions at the particular site. In the assessment made here, it is assumed that infiltration from an adjacent river or stream is sufficient to sustain the yield of wells in time of protracted drought with only small reliance upon water stored in the sediments or local recharge from precipitation.

RECHARGE

As noted, it is likely that sustaining the higher yields will depend almost entirely upon induced filtration from an adjacent river or stream. Local recharge from precipitation on sandy glacial terrane is as much as 1 mgd per square mile, and in such places, assuming that a reasonable amount of storage is present, water may be obtained without dependence upon induced infiltration from streams. However, geologic and hydrologic conditions vary greatly from one site to another and no attempt is made here to generalize on the cost of developing ground water where induced infiltration is not a prime factor. Because the storage potential of stratified glacial sediments is great, and recharge is relatively high, it is not implied that water in significant quantity may not be developed in many places where only local recharge is relied upon.

COST OF WATER

Cost figures are based on various yields that may be obtained from wells ranging from 100 to 1,400 gpm. Pipeline costs are based on a spacing between wells of 500 feet where wells yield 100 gpm and 1,000 feet where the wells have the higher yields shown.

In some instances, it has been found that interference between high yield wells that induce infiltration from a nearby river is so insignificant that wells may be spaced more closely than 1,000 feet apart. In such instances, pipeline costs would be less than shown in the tables. In somewhat few instances, yields of more than 2 mgd may be developed from a single well in glacial deposits.

Tables D-14A-E show costs for water from wells in glacial sediments within the ranges that will commonly be developed for municipal and industrial supplies. It will be noted that for every production well, a test hole of six or eight-inch diameter is also budgeted. In some instances the test hole may be converted into a production well, thus lowering costs somewhat. In other instances, more than one test hole may be necessary.

At each of the stated yields, costs for wells 75 feet and 200 feet deep are given, thus encompassing the depths to which most wells will be drilled.

CHAPTER VI

ECONOMY IN DEVELOPING GROUND-WATER SUPPLIES

CAPITAL EXPENDITURES

The greatest economies in developing ground-water supplies may be gained by proceeding with well construction only after maximum knowledge of the area and the aquifer to be developed is at hand and by constructing the type of well needed in the various environments that will be developed. The savings effected by lack of the proper kind of professional advice, by failing to drill enough test holes or by skimping on the construction of the well itself, will commonly prove costly in the long run, if not immediately.

As brought out above, ground water is very cheap where aquifer potential is commensurate with the demand imposed upon it. It can be shown that small and in some instances, large differences in capital costs become insignificant when cost per thousand gallons to the consumer is calculated. In the final analysis, it is that cost to the consumer that maintains the system and amortizes the initial cost of construction.

With reference to the first point mentioned, proper professional advice, the 15 percent budgeted in the tables for "engineering," provides for such advice. It is firmly believed that expenditure of money thus budgeted will generally yield a "profit"--or, at the very least, will insure that significant losses are not sustained.

TABLE D-14A.--WELLS IN GLACIAL DEPOSITS - CAPITAL COSTS OF WELLS.

Maximum yield (gpm)	Test well or wells	Production well	Total drilling	Screen	Develop	Pump	Test run	House	Sub-total	Eng. & cont.	Total capital cost 1968	Total capital cost 1970
100 gpm	($525) (75')	($750) (75' x 6")	$1,275	$300 5' x 6"	$200 1 day	$1,700 100 gpm	$360 24 hrs	$2,500	$6,335	$1,584 25%	$7,919	$8,71[illegible]
100 gpm	($1,400) (200')	($2,000) (200' x 6")	$3,400	" "	" "	" "	" "	"	$8,460	$2,115 "	$10,575	$11,636
350 gpm	($675) (75')	($1,050) (75' x 8")	$1,725	$715 10' x 8"	$400 2 days	$3,400 350 gpm	$480 24 hrs	$2,500	$9,220	$2,305 25%	$11,525	$12,678
350 gpm	($1,800) (200')	($2,800) (200' x 8")	$4,600	" "	" "	" "	" "	"	$12,095	$3,024 "	$15,119	$16,631
700 gpm	($1,350) (75')	($2,550) (75' x 14")	$3,900	$1,430 20' x 10"	$600 3 days	$5,040 700 gpm	$960 48 hrs	$2,500	$14,430	$3,607 25%	$18,037	$19,841
700 gpm	($3,600) (200')	($6,800) (200' x 14")	$10,400	" "	" "	" "	" "	"	$20,930	$5,235 "	$26,165	$28,782
1,400 gpm	($1,350) (75')	($6,800) (40' x 24", 30' x 18")	$8,150	$2,800 25' x 16"	$1,200 4 days	$8,800 14,000 gpm	$960 48 hrs	$2,500	$24,410	$6,103 25%	$30,513	$33,564
1,400 gpm	($3,600) (220')	($14,600) (40' x 24", 160' x 18")	$18,200	" "	" "	" "	" "	"	$34,460	$8,615 "	$43,075	$47,383

TABLE D-14B.--WELLS IN GLACIAL DEPOSITS - AMORTIZATION AND OPERATIONAL COSTS AND UNIT COST OF WATER.

Yield (gpm)	Depth (feet)	Capital costs (1970)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal.		
								Equip. & maint.	Power	Total
100	75	$ 8,711	$ 627	$ 87	$ 714	$ 1.95	86.4	$.0226	$.009	$.0316
100	200	11,636	838	116	954	2.61	86.4	.0302	.009	.0392
350	75	12,678	913	127	1,040	2.85	300	.0095	.009	.0185
350	200	16,631	1,197	166	1,368	3.73	300	.0124	.009	.0214
700	75	19,841	1,428	198	1,626	4.45	600	.0074	.009	.0164
700	200	28,872	2,079	289	2,368	6.49	600	.0108	.009	.0198
1,400	75	33,564	2,417	336	2,753	7.54	1,200	.0063	.009	.0153
1,400	200	47,383	3,412	474	3,886	10.65	1,200	.0089	.009	.0179

TABLE D-14C.--WELLS IN GLACIAL DEPOSITS - COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS WHERE WELLS YIELD 100 gpm.

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost per 1,000 gal.	
											75 ft.	200 ft.
					Wells yield 100 gpm							
1	0.14	--	--	--	--	--	--	--	86	--	$.032	$.039
2	0.29	$ 3,658	$ 47	$ 3,705	$ 267	$ 9.1	$ 276	$ .76	173	$.0044	.036	.044
3	0.43	8,313	95	8,408	605	21	626	1.72	259	.0066	.038	.046
4	0.58	13,606	142	13,748	990	34	1,024	2.81	346	.0081	.040	.047
5	0.72	18,886	189	19,075	1,373	47	1,420	3.89	432	.0090	.041	.048
10	1.44	52,136	426	52,562	3,784	95	3,879	10.62	864	.0122	.046	.051
20	2.88	148,295	899	149,194	10,742	370	11,112	30.44	1,728	.0176	.049	.057
40	5.76	392,350	1,845	394,195	28,382	980	29,372	80.47	3,460	.0232	.056	.063

TABLE D-14D.---WELLS IN GLACIAL DEPOSITS - COST OF CONNECTING PIPE AND TOTAL COST OF WATER IN MULTIPLE WELL SYSTEMS.

No. of wells	System capacity	Daily discharge	Added pipe cost 1/	Total cost per 1,000 gal. 75 ft.	200 ft.
		Wells yielding 350 gpm			
1	0.5	0.3	- -	.0185	.0214
2	1.0	0.6	.003	.022	.026
3	1.5	0.9	.005	.023	.036
4	2.0	1.2	.005	.024	.027
5	2.5	1.5	.008	.026	.029
10	5.0	3.0	.011	.030	.033
20	10.0	6.0	.016	.035	.038
40	20.0	12.0	.022	.040	.043
65	32.5	19.5	.027	.046	.048
80	40.0	24.0	.033	.052	.054
		Wells yielding 700 gpm			
1	1.0	0.6	- -	.016	.020
2	2.0	1.2	.0017	.018	.022
3	3.0	1.8	.0031	.019	.023
4	4.0	2.4	.004	.020	.024
5	5.0	3.0	.0067	.023	.026
10	10.0	6.0	.007	.024	.027
20	20.0	12.0	.011	.027	.030
33	33.0	19.8	.014	.030	.033
40	40.0	24.0	.025	.041	.045
		Wells yielding 1,400 gpm			
1	2.0	1.2	- -	.0153	.0179
2	4.0	2.4	.0012	.0168	.0191
3	6.0	3.6	.0020	.0178	.0199
4	8.0	4.8	.0026	.0179	.0205
5	10.0	6.0	.0031	.0184	.0210
10	20.0	12.0	.0049	.0202	.0228
16	32.0	19.2	.0662	.0215	.0241
20	40.0	24.0	.0076	.0229	.0255

1/ Pipe cost data taken from table D-12D, E

TABLE D-14E.--SUMMARY OF CAPITAL COSTS OF MULTIPLE WELL SYSTEMS IN GLACIAL SEDIMENTS.

No. of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells		Cost of pipeline a/	Total capital costs	
			75 ft.	200 ft.		75 ft.	200 ft.
			Wells yielding 100 gpm				
1	0.14	.09	8,711	11,636	- -	8,711	11,636
2	0.29	.17	17,422	23,272	3,705	21,127	26,977
3	0.43	.26	26,133	34,908	8,404	34,537	43,312
4	0.58	.35	34,840	46,544	13,748	48,588	60,292
5	0.72	.43	43,555	58,180	19,075	62,630	77,255
10	1.44	.86	87,110	116,360	52,562	139,672	168,922
20	2.88	1.73	174,220	232,720	149,194	323,414	381,914
40	5.76	3.46	348,400	465,440	394,195	742,595	859,635
			Wells yielding 350 gpm				
1	0.5	0.3	12,678	16,631	- -	12,678	16,631
2	1.0	0.6	25,356	33,262	9,418	34,774	42,680
3	1.5	0.9	38,034	49,893	20,804	58,838	70,697
4	2.0	1.2	50,712	66,524	34,279	84,991	100,803
5	2.5	1.5	63,390	83,155	54,802	118,192	137,957
10	5.0	3.0	126,780	166,310	166,302	293,082	332,612
20	10.0	6.0	253,560	332,620	475,610	729,170	808,230
40	20.0	12.0	507,120	665,240	1,280,513	1,787,633	1,945,753
65	32.5	19.5	824,070	1,081,015	2,584,870	3,408,940	3,665,885
80	40.0	24.0	1,014,240	1,330,480	3,887,091	4,901,331	5,217,571
			Wells yielding 700 gpm				
1	1	0.6	19,841	28,782	- -	19,841	28,782
2	2	1.2	39,680	57,744	10,402	50,082	68,176
3	3	1.8	59,520	86,346	27,401	86,921	113,747
4	4	2.4	79,360	115,128	47,884	127,190	163,012
5	5	3.0	99,205	143,910	71,003	170,208	214,913
10	10	6.0	198,410	287,820	216,311	414,721	504,131
20	20	12.0	396,800	577,440	622,907	1,019,707	1,200,347
33	33	19.8	654,753	949,806	1,292,595	1,947,348	2,242,401
40	40	24.0	793,600	1,115,128	1,935,780	2,729,380	3,050,908
			Wells yielding 1,400 gpm				
1	2	1.2	33,564	47,383	- -	33,564	47,383
2	4	2.4	67,128	94,766	13,701	80,829	108,467
3	6	3.6	100,692	142,149	35,461	136,153	177,610
4	8	4.8	134,256	189,532	62,249	196,505	251,781
5	10	6.0	167,820	236,915	92,137	259,957	329,052
10	20	12.0	335,640	473,830	284,061	619,701	757,891
16	32	19.2	537,024	758,128	586,619	1,123,643	1,344,747
20	40	24.0	671,280	947,660	887,258	1,558,538	1,834,918

a/ From table D-12D

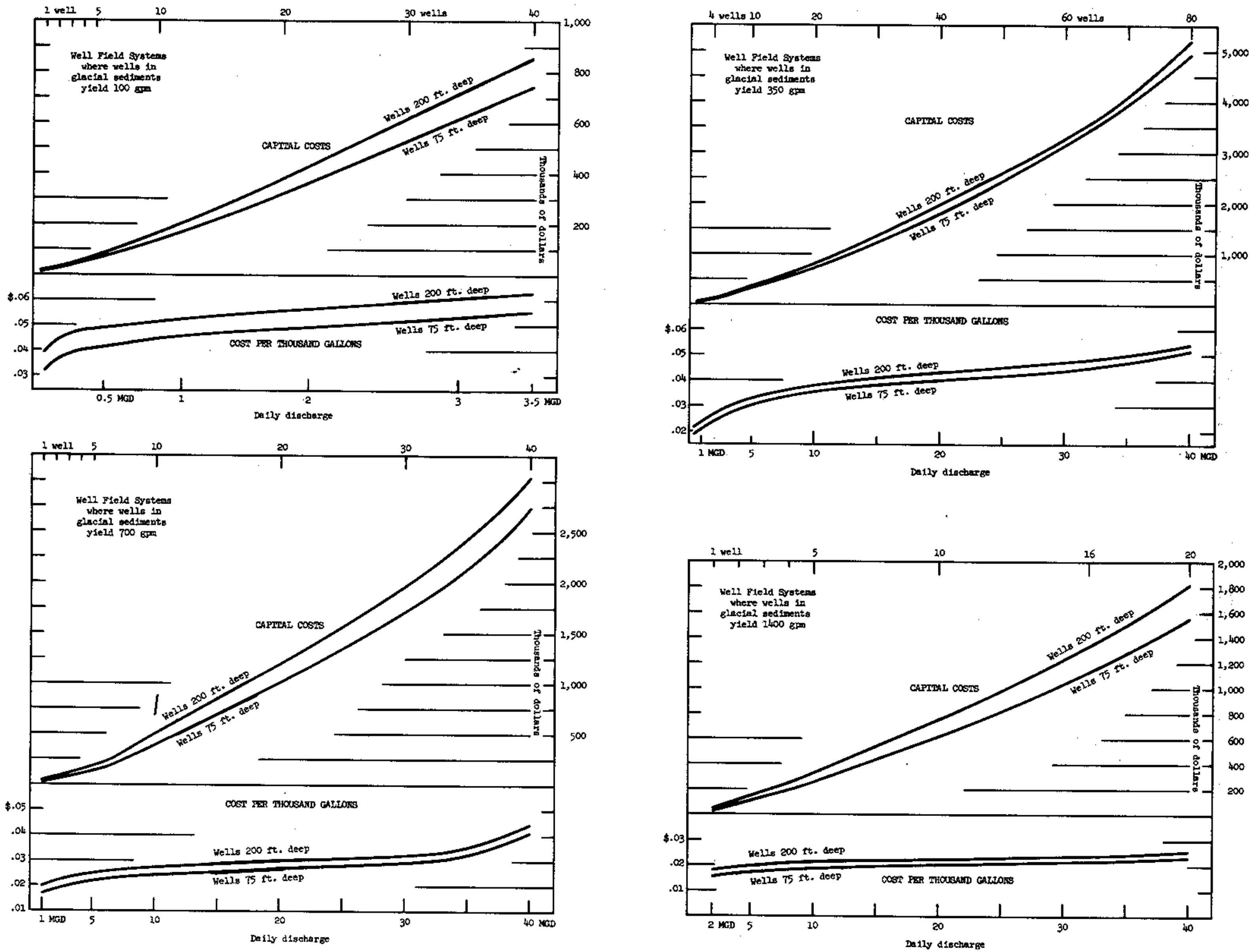


Figure D-18.--Graphs showing capital costs and cost per thousand gallons of water from wells in glacial sediments.

Many well installations have been completed, some at quite reasonable cost, without the advice of professionals knowledgeable in the field of ground-water development. However, when overall results are assessed, it is quite clear that it is desirable and good economy to provide for professional advice before embarking on a well-drilling program, however small. From a cost point of view, the ideal well-development program will be based on the combined advice of a ground-water hydrologist, an engineer, and a knowledgeable member of the well-drilling profession. Thoroughly objective advice may be hard to come by, but it should be sought.

Considering the water supply for a small municipality, assume that a well costs $12,800 (table D-14A) and yields 150 gpm. Water at the wellhead will be furnished at three cents a thousand gallons. If the 15 percent "engineering" cost were deducted, the cost to the consumer would be decreased less than two-tenths of a cent per thousand gallons. The saving can hardly appear great enough to warrant the risk of proceeding on the basis of general knowledge possessed by personnel who are not versed in various aspects of ground-water hydrology. Ground-water is not a simple discipline and knowledge of the science (or preferably, the art) is no more well-known to many technical people and some self-styled authorities than is the workings of a TV set to the average householder.

To save money by completing wells in granular sediments utilizing slotted pipe instead of screen, developing a well open end, or failing to develop a well fully after screen is in place is literally asking for trouble and expense. If we consider a well in glacial sediments, 200 feet deep and yielding 700 gpm, water at the wellhead would cost about 2.0 cents per thousand gallons (table D-14A). Looking at the not insignificant item of a well screen, $1,970 budgeted ($1,430 x 25% engineering and contingency x 10%), how much might be saved by not using a screen? The cost of the screen works out to six tenths of a cent per thousand gallons if the well produces 700 gpm 60 percent of the time. It would obviously be undesirable here to try to save the six tenths of a cent in view of the probability of getting half or one-fourth the potential yield, and an installation where water might cost almost four times as much and where the well might not be permanently stabilized.

The proper use of screens in wells in unconsolidated formations cannot be overemphasized. Directions on slot-size and length of screen to be used are commonly furnished by the manufacturer and is discussed in available handbooks. It is clear from a calculation of cost aspects that in some instances the difference in capital costs, according to possible methods of finishing the well, is a relatively minor aspect of the problem. What is critical is the fact that proper design and small increased capital cost of screen may easily enough result in 25 percent more available water. In some circumstances the extra water thus produced may eliminate the need for an additional well and connecting pipeline at a saving of possibly many thousands of dollars.

TEST DRILLING

In the planning of a well field it seems clear that from the preceding discussion that drilling of more than a minimum of test holes may be quite rewarding in financial terms.

Looking at the cost elements of test holes relative to completed producing wells, it is seen that a 400-foot test hole in hard rock will cost about $2,700 (including engineering and contingency costs plus 10%), whereas a 400-foot hole completed as a producing well, yielding 75 gpm, will cost about $9,200. Where the producing well yields 300 gpm, total costs would be about $12,100. The cost of a test hole, therefore, is fairly low relative to the cost of a completed well. Further, because the cost of test holes is a lesser factor in developing a well field, it may be worthwhile to abandon test wells that fail to yield the average volume expected in the formation being drilled.

We might compare results obtained by drilling a minimum number of holes in the Triassic sandstone and conglomeratic beds where an average yield of 150 gpm may be expected. If 4 holes were drilled and the average yield was 75 gpm, the cost of completing them as producers would be about $36,850 plus connecting pipeline, $39,900, a total of $76,750.

On the other hand, if 8 test holes were drilled and 4 of these attained an average yield of 150 gpm, the completed wells and test holes would cost $51,340 and connecting pipeline $59,180. Thus, for a total of $110,500, twice as much water would be produced as for $76,750. If it were necessary to drill 12 test holes to achieve the 150 gpm yields from 4 wells, the total cost would be about $123,300 as compared to $76,750 for completing the initial 4 low yield wells as a source of supply. Thus it would seem that making do with the results of initial test drilling would be a shortsighted economy where there is reason to expect that higher yields can be developed in the area.

It may be seen that two cost factors come into play in these examples, both of which are to be compared to the relatively low cost of test drilling. One is the cost of finishing a test hole as a producing well. A pump in a well yielding 150 gpm will only cost about 20% more than the pump installed in a 75 gpm well but the 150 gpm well yields twice as much water. In terms of cost per thousand gallons the difference is between, roughly, 5¢ a thousand gallons and 3¢ a thousand gallons. The gain of 2¢ per thousand is a 40% decrease in final costs.

The foregoing remarks point out the desirability of adequate test drilling. It should not be inferred from the discussion that indiscriminate drilling should be undertaken blindly in the hope of developing larger yield wells than those obtained in a minimum program. Rather, expansion of an initial program should be based on the following considerations:

1. The initial very few holes indicate that average yields for the rock type have not been developed.

2. Advice from professional hydrologists show clearly or suggest that more likely locations have not been tested.

3. Pipeline costs to more likely locations would not be less than the cost of developing lower yield wells closer to the point of use.

In any event, the moderate cost of test drilling, where a ground-water supply appears to be a logical answer to a need, may be considered as a simple insurance expenditure where an alternative supply would be very costly.

The yield of any one well in consolidated rock and hence, the cost of producing water from any one well cannot be predicted. In the cost tables given it is assumed that it will be necessary to drill two test holes to locate one well that will have the average yield characteristic of municipal and industrial wells in that formation. Nevertheless, in developing a well field in consolidated rock, bad judgment or bad luck may prevail in some instances and it may be found desirable or necessary to drill more test holes to obtain adequate water. This may also be a problem where wells are to be developed in glacial deposits.

To show, in a different way, the relatively low cost of test drilling, let us assume that in a particularly unfavorable crystalline rock area, a small water supply is imperative. The diagram (fig. D-19) shows the capital cost and cost per thousand gallons of water where ten test holes were drilled and one or more of these are completed as production wells yielding 75 gpm.

The cost of a 400-foot test hole is taken as $2,700 and the cost of a completed well as $11,914 less $2,700, about $9,200.

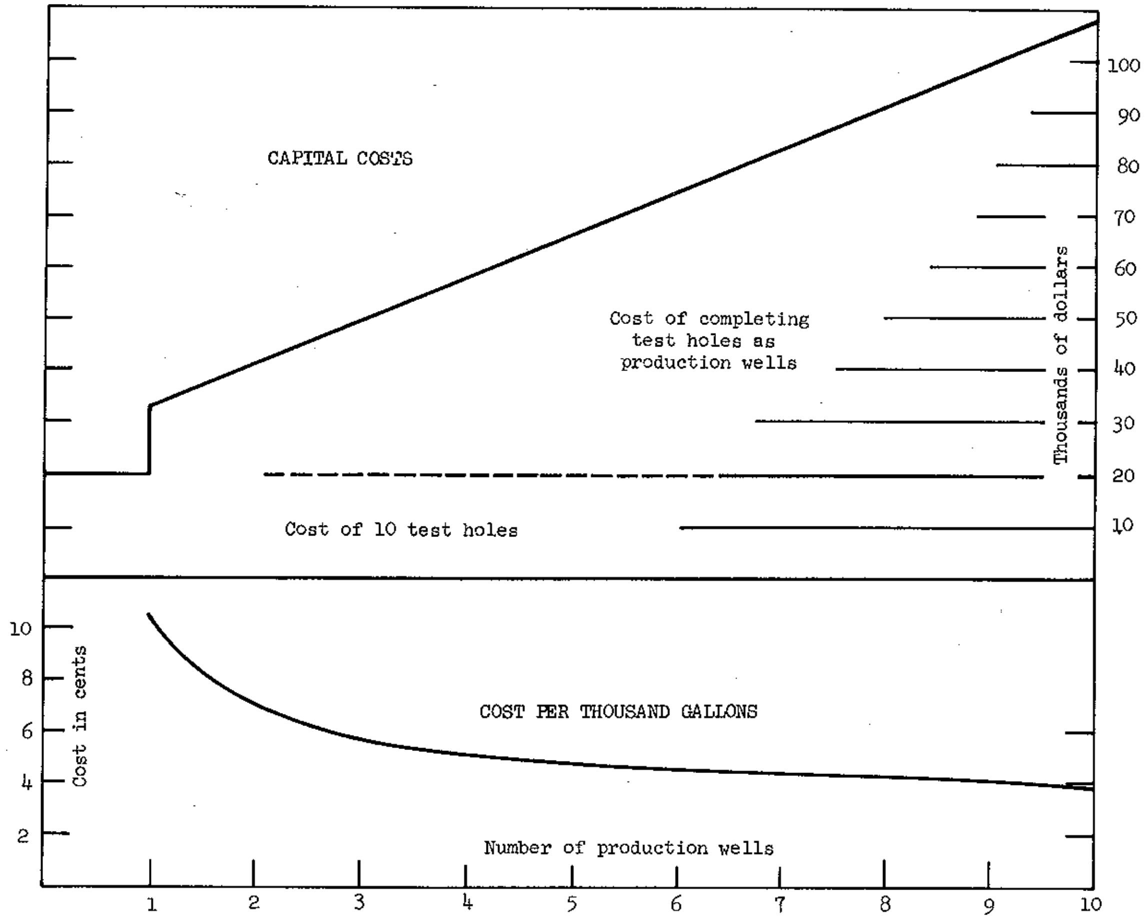


Figure D-19.--Cost of water where one or more of 10 test holes are completed as producing wells, each yielding 75 gpm.

Where only one of the ten test wells can be finished as a producing well with a yield of 75 gpm, the cost of water at the wellhead is about 11 cents per thousand gallons. Where two wells out of ten are successful the cost per thousand gallons is about 7¢ a thousand, and so on.

Note that only small gains in cost per thousand gallons are achieved as the degree of success rises from four successful wells out of ten test holes to the point where all holes are capable of being completed as producers. This relationship shows rather clearly that only moderate success in test drilling is necessary to obtain a well-water supply at a rather reasonable cost, or conversely, the cost of drilling "extra" test holes is small where a moderate success is finally achieved.

It should be noted that each unsuccessful test hole drilled adds 82 mills ($.0082) to the cost per thousand gallons to the water eventually produced from one 75 gpm well pumping 60 percent of the time. Costs would be somewhat less if test holes were abandoned as nonproductive at depths of 250 to 350 feet.

In the most crystalline rock areas it is unlikely that more than two or three wells would have to be drilled to develop 75 gpm if sites are chosen by a trained ground-water hydrologist. Most of the conspicuous failures (low yields) in crystalline rock areas may be ascribed to the tendency to locate wells on massive rock hilltops.

In exploring glacial deposits that may not be particularly favorable, the cost of each abandoned 75-foot test hole would add only 16 mills ($.0016) per thousand gallons to the cost of water from the one well yielding 100 gpm.

Costs of pipeline have not been considered in the foregoing discussion.

Test drilling by the jetting method. It is the practice in some areas to drill test holes in glacial sediments with a small diameter jetting rig. This practice, in the writer's considered opinion, based on considerable field experience, is one of the most shortsighted "economies" that might be employed. The cost of such jet drilling is about $2.75 a foot, as opposed to a nominal about $7.75 a foot for drilling 6-inch diameter hole where casing is recovered. If four locations were explored utilizing a 6-inch percussion drill to a depth of 100 feet, and one of the test holes could be converted into a producing well, the total cost might be $2,910 for the abandoned holes and $9,050 for the producing well, a total of $11,960. If on the other hand, 4 small diameter holes were jetted and subsequently a 6-inch well was drilled at one of the sites, total costs would be $10,150, that is, the total job would have cost $1,810 less.

However, in drilling by the jetting method, there is no assurance whatever of being able to penetrate the full thickness of the glacial sediments. Tight fine sand, till or boulders may prevent a wash drill from attaining full penetration and hence, in many instances, desirable water-bearing formations at depth will not be located and a considerably more expensive supply might have to be developed. Shallow aquifers may not be present and in any event, deeper aquifers will permit construction of wells having a greater available drawdown and greater storage potential.

In drilling in the glacial sediments in the Montpelier, Vermont area, it was found (Arthur L. Hodges, Jr., written communication, 1971) that the "wash drill" penetrated fine silty sand quite well but failed to reach bedrock in gravel or till. In one location wash drill penetration failed at 63 feet whereas cable tool drilling established depth of bedrock at 87 feet. In a second location 3 wash drill holes advanced to a depth of only 49 feet when bedrock was reached by the cable tool at 100 feet.

A "saving" of 15 percent capital cost in the example cited would seem to be a poor risk to take when failure might mean increasing the capital costs of obtaining a supply by several orders of magnitude. Expressed in terms of cost per thousand gallons, where the producing well yields 100 gpm and operates 60 percent of the time, the "saving" becomes even less justifiable. The $1,810 saved--if drilling were successful using the jet drill--would lower the cost of water produced by less than 4 mills ($.004) per thousand gallons. Going even farther, if the average water consumer uses 150 gallons per day, a family of three people would use about 13,000 gallons a month at an additional cost of 5 cents a month. Average household consumption is more likely about 55 gallons a day, in which case the extra cost would be less than 2 cents a month. The additional 2 cents or even 5 cents a month could hardly be thought of as an unreasonable price to pay for having a job done properly and avoiding the risk of a much higher cost supply.

Looking at the extremes inherent in these options, there is a fair chance that the first test hole drilled 6-inches in diameter could be converted into a producing well, whereas a great many jet drill test holes might be put down without ever finding a water-bearing stratum.

SPECIFICATIONS

From time to time it appears that detailed specifications for a production well are drawn up before the aquifer characteristics are known. This practice will ordinarily not be in the best interests of the developer from a cost point of view. Even where development of water in a less complex rock environment is concerned, preliminary slim-hole drilling may indicate that certain straightforward preconceived measures should be eliminated or modified. In an environment of glacial or coastal plain granular sediments, much may be gained from a discussion of the test drilling results before the production well specifications are decided upon. The hydrologist, the engineer, or particularly the well drilling representative may have suggestions to offer that will result in a lower cost per thousand gallons to the consumer. Specifically, the slot size and length of the well screen cannot be determined in advance of test drilling. The dimensions of the casing in the production well may be subject to decision after the fact of test drilling. The diameter of the upper part of a production well will be designed to accommodate a certain sized pump and the lower portion of the casing will permit installation of the appropriate screen. Gravel packing (actually, sand packing) may be desirable or even necessary where only fine sediments are present. Special conditions may call for departure from common practice.

Development time may be subject to modification as final stages of work on the production well proceeds. This is of utmost importance in the somewhat shallow water table wells in glacial deposits where available drawdown may be severely limited. If three days "extra" development were applied to a well producing initially 100 gpm at a cost of $200 a day and if the yield of the well increased by 25 gpm as a result of the additional development, the "extra" 25 gpm would cost only about 3 mills per thousand gallons plus cost of lift, another fraction of a cent. Further, the additional 25 gpm might, in some circumstances, be sufficient to provide for the extra capacity required for peak loads, or, in multiple well developments, four 125 gpm wells would provide as much water as five 100 gpm wells at a real savings in capital costs (including pipeline costs) as well as in cost per thousand gallons.

CONNECTING PIPE

Although the optimum pipe diameter to be chosen in any given situation is the task of the design engineer and will be predicated upon present and future needs of the consumer and the geologic and hydrologic conditions of the area, the following remarks seem relevant in this paper.

Labor cost is the largest item in building pipeline. It would seem then that the additional cost incurred in laying line large enough to carry the full capacity of the wells rather than the minimum diameter required by present demand, would yield substantial gains in meeting peak demands, for fire protection and in lower power costs. According to data given in figure D-14, line carrying 70 gpm costs about $36,000 a mile installed, but a line carrying twice as much water will cost only $42,000. Pipe carrying 2 mgd (1,400 gpm) costs about $72,000 a mile, whereas a pipe of twice that capacity will cost about $93,000 a mile. Regardless of price charges due to inflation or other factors, the relative costs will be much the same in the future. Thus, all pipeline connecting wells should be the recommended size for delivering the maximum yield of all wells operating simultaneously and further, it will be good economics to anticipate future needs and provide for additional carrying capacity of the trunkline in the initial layout. In such instances, hydrologic advice must be obtained to ascertain if additional supplies can be made available along the proposed trunkline at some future date.

Feeder lines from a trunkline to small yield wells and the small yield wells themselves are relatively expensive. Test drilling to locate higher-than-average yield wells and to eliminate lower yield wells will probably be good economics from the point of view of minimizing pipeline costs. To show pipeline costs in relation to yields of wells, we may consider a limestone area where $\frac{1}{4}$ mile laterals are laid to two wells that yield 150 gpm each. Pipe would cost about $19,400 and the wells about $25,750, say a total of $45,150. If one 300 gpm well could be developed, costs would be $\frac{1}{4}$ mile of lateral at about $11,870 and one well installation at $14,960 or a total of $26,830. The saving in capital cost of pipeline here is $7,530.

The difference in total cost here would be about $18,320, enough to pay for the drilling of about 2,700 feet of exploratory slim-hole. That is to say, if initial drilling has developed a well with a 150 gpm yield, but there is a good chance of developing a 300 gpm well, the cost of drilling the 150 gpm well may be charged off after which more than 2,300 feet of exploratory drilling may be justified in seeking to develop a 300 gpm well. Unfortunately, the yield of any one well in hard rock cannot be predicted, and, in the example given, success in locating the higher yield could not be guaranteed. However, in drilling 5 or 6 more test holes, even if a 300 gpm well could not be located, the probability is very high that 2 or more wells would have at least average yields of 150 gpm, in which case no real financial loss would be sustained.

For a small municipal development, it is estimated on the basis of assumptions used here that connecting pipe for a 1.28 mgd system delivering 0.78 mgd from wells producing 75 gpm each would cost $187,530, whereas in a well field where wells yield 300 gpm, the cost of pipeline required would only be about $70,700.

CHAPTER VII

CONCLUSIONS

Ground water at the wellhead is relatively inexpensive. In multiple-well fields ground water is generally inexpensive where the capability of the aquifer is commensurate with the total demand. Due to the cost of connecting pipe in multiple-well fields, production of more than one or two million gallons of ground water a day in some areas may be impractical but in the more favorable aquifers development of several tens of millions of gallons a day may not be prohibitively expensive. Where large water requirements consist of many small to moderate demands at distinctly separate points, ground-water supplies may serve admirably from a cost point of view. Where a lesser but still large requirement must be satisfied at one point, development of ground water may not be practicable except as a supplementary or emergency supply.

Specialized knowledge and judgment on the part of the ground water hydrologist, the engineer and the well driller is necessary in considering both the capabilities of the aquifer and the layout of the system. Only when these areas of competence are represented will the most practical and most economic supply be developed.

With reference to the writer's specialized field of competence, it is clear that the conclusions reached by a ground-water hydrologist after study of any plan for a ground-water supply are vital if real economies and a maximum supply of ground water are to be developed. The ground-water hydrologist will not only interpret the geological framework and the hydrologic principles involved in any area under consideration, but as exploration proceeds will also weigh costs of further test hole drilling and chances of greater success against final production well and pipeline costs.

Data and discussions presented in Part II of this report are intended to assist him in this field.

In the planning of many supplies the ground-water hydrologist will be alert to possibilities of artificial recharge in areas of heavy ground-water withdrawal with the intent of pointing out means of insuring a large safety factor, of gaining greater total ground-water availability or minimizing pipeline costs and the number of production wells. Insofar as the technique of artificial recharge is concerned he will necessarily work closely with engineering personnel regarding costs of surface structures that might be necessary.

CHAPTER VIII

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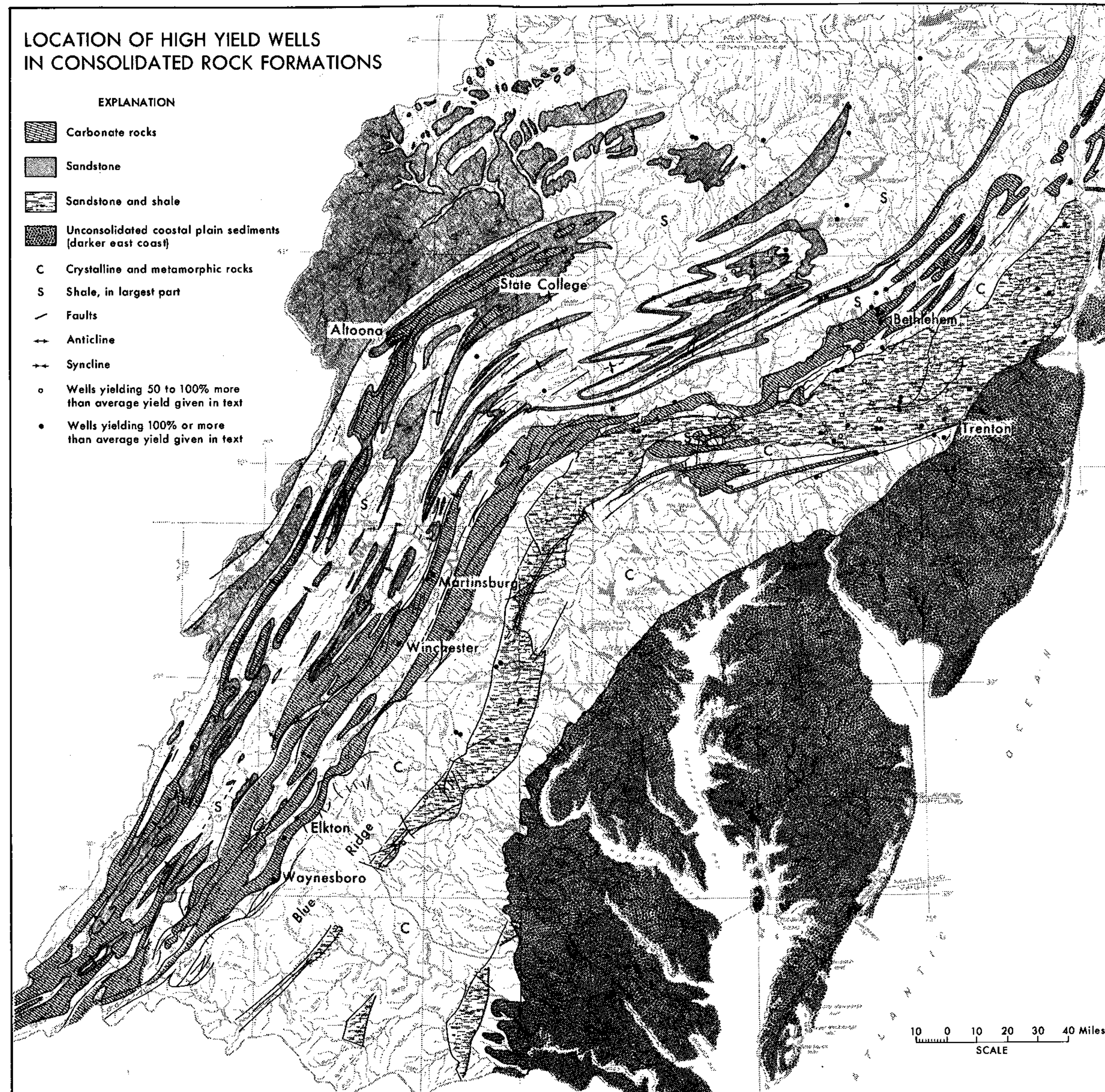

Figure D-9.--Map showing relationship of high-yield wells to geologic structure.

FEBRUARY 1967

Plate D-1A

NORTH ATLANTIC REGIONAL WATER RESOURCES STUDY

U. S. DEPARTMENT of the INTERIOR
GEOLOGICAL SURVEY

April 1970
Rev. March 1971

GROUND WATER FAVORABILITY MAP of the NORTH ATLANTIC REGION

GLACIAL DEPOSITS

LEGEND

- Deposits capable of yielding more than 1 mgd to properly constructed wells. Sustained yields in multiple well developments will depend largely upon availability of induced recharge from adjacent rivers. On Long Island sustained yields depend upon local recharge from precipitation.
- Deposits capable of yielding generally less than 1 mgd to properly constructed wells.
- Areas of widespread stratified deposits whose capability to supply ground water is not known. Yields of up to a few hundred gallons a minute per well may be possible in many places and up to 1 mgd may be available in a few places where recharge from larger streams will be induced by heavy pumping.
- Suggested locations of excellent water-bearing glacial deposits. Only highly generalized data are available in these areas and the map simply suggests that large yields from wells will commonly be available where this pattern is shown.

LEGEND

- NAR BOUNDARY
- SUB-REGION BOUNDARY
- BASIN OR AREA BOUNDARY
- BOUNDARIES OF SUB-BASINS WITHIN NUMBERED AREAS
- COUNTY BOUNDARY

Issued by NAR Group, NAD, Corps of Engineers
Base Map by USDA - Soil Conservation Service
Cartographic Unit, Hyattsville, Maryland January 1967